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Manned and unmanned aircraft effectiveness in fast attack craft / fast inshore attack craft ASUW kill chain execution

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

MANNED AND UNMANNED AIRCRAFT EFFECTIVENESS IN FAST ATTACK CRAFT / FAST INSHORE ATTACK CRAFT ASUW KILL CHAIN EXECUTION

by

Alexander D. Anderson

September 2016

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Co-Advisor: Michael P. Atkinson

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The ability of unmanned aerial vehicles to execute intelligence, surveillance, reconnaissance, and targeting and strike missions creates a trade-space decision for naval aviation programmatic decision makers. In the military's current fiscal climate, manned and unmanned aircraft compete for limited funding. This study takes a simulation approach using the simulation modeling framework based on intelligent objects (SIMIO) environment to model a fast attack craft/fast inshore attack craft anti-surface warfare expanded kill chain. It tests and analyzes multiple manned and unmanned aircraft configurations. In the evaluation of unclassified concepts of operation and use of unclassified data sources, results indicate that aircraft attrition due to hostile weapon engagements is the dominant factor in the determination of concept of operation efficiency. Based on the operational environment, low cost and less capable unmanned aircraft provide an alternative to the increased survivability of manned aircraft or more capable and higher cost unmanned aircraft. We provide quantifiable metrics that enable the efficient and effective selection of aircraft to execute fast attack craft/fast inshore attack craft anti-surface warfare kill chains.

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MANNED AND UNMANNED AIRCRAFT EFFECTIVENESS IN FAST ATTACK CRAFT / FAST INSHORE ATTACK CRAFT ASUW KILL CHAIN EXECUTION

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ABSTRACT

The ability of unmanned aerial vehicles to execute intelligence, surveillance, reconnaissance, and targeting and strike missions creates a trade-space decision for naval aviation programmatic decision makers. In the military's current fiscal climate, manned and unmanned aircraft compete for limited funding. This study takes a simulation approach using the simulation modeling framework based on intelligent objects (SIMIO) environment to model a fast attack craft/fast inshore attack craft anti-surface warfare expanded kill chain. It tests and analyzes multiple manned and unmanned aircraft configurations. In the evaluation of unclassified concepts of operation and use of unclassified data sources, results indicate that aircraft attrition due to hostile weapon engagements is the dominant factor in the determination of concept of operation efficiency. Based on the operational environment, low cost and less capable unmanned aircraft provide an alternative to the increased survivability of manned aircraft or more capable and higher cost unmanned aircraft. We provide quantifiable metrics that enable the efficient and effective selection of aircraft to execute fast attack craft/fast inshore attack craft anti-surface warfare kill chains.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

$M	dollars in millions
µm	micrometers
A2/AD	anti-access area denial
ALT	altitude
AO	area of operations
APKWS	Advance Precision Kill Weapon System
APUC	average procurement unit cost
ASUW	anti-surface warfare
ASW	anti-submarine warfare
AVE	average
BY	base year
CBRD	chemical, biological, radiological defense
CCS	common control station
CEP	circular error probable
CG	guided missile cruiser
CNAF	Commander Naval Air Forces
COBRA	Coastal Battlefield Reconnaissance and Analysis
CONOPS	concepts of operation
COP	common operating picture
CY	current year
DDG	guided missile destroyer
DOD	Department of Defense
DON	Department of the Navy
DOT&E	Office of the Director, Operational Test and Evaluation
DSB	Defense Science Board
EFL	effective focal length
EO	electro-optical
EO/IR	electro-optical/infrared
F2T2EA	find, fix, track, target, engage and assess
FAC	fast attack craft

FIAC	fast inshore attack craft
FRP	full rate production
FT	feet
FY	fiscal year
GAO	Government Accountability Office
GCS	ground control station
GPS	global positioning system
GSD	ground separable distance
HSCWINGPAC	Helicopter Sea Combat Wing Pacific
HH	time in hours
HRS	hours
IR	infrared
ISR	intelligence, surveillance, reconnaissance
ISR&T	intelligence, surveillance, reconnaissance and targeting
KCAS	knots calibrated airspeed
KTS	knots
LCC	life cycle cost
LCS	littoral combat ship
LPD	amphibious transport dock
LRIP	low rate initial production
LSD	landing ship dock
M	meters
MCM	mine counter measures
MDA	maritime domain awareness
MM	time in minutes
MOE	measure of effectiveness
MOP	measure of performance
M/S	meters per second
MSL	mean sea level
MTBF	mean time between failures
MTTR	mean time to repair
NAVAIR	U.S. Navy Naval Air Systems Command

NIIRS	National Image Interpretability Rating Scales
NM	nautical miles
O&S	operating and support
PEO	program executive office
PMA	program manager air
PP	pixel pitch
ROI	return on investment
RPV	remote piloted vehicle
RTD&E	research, testing, development and evaluation
SAG	surface action group
SAM	surface to air missile
SAR	selected acquisition report
SE	systems engineering
SIMIO	simulation modeling framework based on intelligent objects
SR	slant range
SS	time in seconds
STUAS	small tactical unmanned aircraft system
SW	sweepwidth
TD	technical directive
TOF	time of flight
U&W	unmanned aviation and strike weapons
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
USMC	United States Marine Corps
USN	United States Navy
YR	year

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THESIS DISCLAIMER

The reader is cautioned that the simulation and results presented in this research are based on unclassified and notional concepts of operation and data. As such, the results of this study may differ significantly from the performance and operation of fielded systems and aircraft. Any application of these results without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

Due to their persistence, versatility and reduction of risk to personnel, unmanned aerial vehicles (UAVs) are an integral part of Department of Defense military operations. The performance of UAVs in missions ranging from intelligence, surveillance, reconnaissance and targeting to the execution of precision strikes demonstrate their capability to act as a force multiplier at both the operational and tactical level. Operational success has led to increased UAV funding, research and development, procurement and integration into the battlespace.

Ultimately, under increased Department of Defense budgetary pressure, the value of UAVs will be determined by their return on investment versus an equivalently mission-capable manned aircraft. In order to determine the return on investment, Naval Air System Command program decision makers and operational commands require the capability to fully quantity the costs and achievable combat power of various aviation platforms in order to increase the validity and effectiveness of programmatic and operational decisions. Despite this need for cost-wise validation of UAVs, the current methodology utilized to simulate and evaluate kill chain success lacks the key metric of cost and excludes the contributions generated through multiple kill chain executions per sortie (Dunaway 61).

This study evaluates a sub-set of operational or in procurement UAVs and manned aircraft in the execution of expanded fast attack craft (FAC)/fast inshore attack craft (FIAC) anti-surface warfare (ASUW) kill chains to answer the questions:

- What is an effective UAV and manned aircraft deployment force structure in order to achieve operational FAC / FIAC ASUW mission requirements?
- Given fixed operational requirements, do UAVs provide a cost effective alternative to manned aircraft when operated in a contested ASUW environment?
- What is the added value of UAVs in the execution of an expanded end-to-end ASUW kill chains?

This study takes a simulation approach with the simulation modeling framework based on intelligent objects (SIMIO) environment to model a fast attack craft / fast inshore attack craft ASUW expanded kill chain. We construct a simulation model of an expanded kill chain that includes traditional find, fix, track, target, engage and assess events and incorporate unclassified or notional aircraft sensor performance, maintenance activities, aircraft reliability and ordnance performance.

The study considers the execution of a FAC/FIAC ASUW expanded kill chain to determine efficient combinations of manned and unmanned aircraft and evaluates the performance of three currently operational or in procurement aircraft: the MH-60S Knighthawk, the MQ-8C Fire Scout and the RQ-21A Blackjack. We choose the aircraft configurations based on unclassified Naval Air System Command and Helicopter Sea Combat Wing Pacific concepts of operation (CONOPS) and evaluate proposed future CONOPS employing the integration of RQ-21A aircraft.

The study conducts 132,000 simulations across over 200 modeling parameters and variables to represent the behavior of the modeled aircraft and a notional RED threat. The simulation results provide information on the performance of the evaluated aircraft configurations based on their cost-wise execution of kills chains and their ability to effectively destroy enemy forces, reduce enemy forces combat power and timely detect both neutral and enemy forces.

The decisions to procure, deploy, and operationally employ manned and unmanned aircraft represent significant naval aviation programmatic decisions. This study provides a methodology and through the results of simulated kill chains informs decision makers to better equip the warfighter. Below we summarize the primary findings of the study:

- Unmanned aircraft provide a viable and cost effective alternative to manned aircraft in the execution of FAC / FIAC ASUW kill chains.
- Aircraft attrition is the dominant factor in the determination of kill chain efficiency. The pursuits of combat survivable or low cost aircraft provide valid avenues to achieve cost efficient kill chain execution.

- Improvement of aircraft sensor capabilities provides the most effective method to reduce aircraft combat losses and attrition costs.

- Aircraft sortie duration and ordnance payload impact the ability to reduce enemy combat power.

This study presents an innovative approach to analyzing kill chain effectiveness through the incorporation of aircraft maintenance, reliability and cost. By evaluating the relationship between operational effectiveness and cost efficiency this study enables exploration of the unmanned and manned aircraft trade-space.

In conclusion, manned and unmanned aircraft will continue to serve vital functions across the spectrum of aviation missions. In the military's current fiscal climate, manned and unmanned aircraft will compete for the limited funding. This thesis tests and analyzes vast simulations of multiple manned and unmanned aircraft configurations. The results provide quantifiable metrics that enable the efficient and effective selection of aircraft to execute FAC / FIAC ASUW kill chains.

Reference

Dunaway, David. *Creating Integrated Warfighting Capabilities Acquisition.* Connection Community, August 2013, 61. *Defense Acquisition University*. acc.dau.mil/adl/en-US/678171/file/74613/%202013%20August%20-%20Creating%20Integrated%20Warfighting%20%20Capabilities_D.%20Dunaway.pdf. Accessed 22 March 2016.

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When I commenced the background research and initial modeling of this thesis, I quickly realized that I had underestimated the difficulty and challenge of the task that was ahead of me. An intertwined partial understanding of search theory, cost estimation, applied physics, and simulation modeling replaced my initial thoughts of a simple and easily constructed academic effort. My need for assistance and guidance became readily apparent. The completion of this daunting task could not have been possible without the knowledge, assistance and tremendous patience of several key people that deserve special recognition.

First, I would like to thank Professor Atkinson. His understanding and ability to apply complex operational research theories pushed my research to levels I did not imagine possible. The weekly meetings, white board scribbling, and limitless editing and re-editing of my convoluted and often misguided writing ensured the success of this thesis.

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Captain Kline, thank you. Your knowledge of naval operations tied my work to the needs of the Navy. Through your efforts, I hope that I have provided the Navy with an academic product that has real value and tangible benefits.

I never imagined that my thesis would be dependent on my knowledge of applied physics. Without Professor Kapolka, abstract and imagined numbers would be the foundation of my calculations. Her untiring willingness to answer emails, provide hand-drawn diagrams and explain difficult concepts in terms that even I could understand enabled my theoretical concepts to mirror reality.

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I. INTRODUCTION

> Unmanned systems, particularly autonomous ones, have to be the new normal in ever-increasing areas.
>
> —Ray Mabus,
> U.S. Secretary of the Navy

A. PURPOSE

The purpose of this research is to provide a method for the Department of the Navy (DON) to more efficiently deploy manned aircraft and unmanned aerial vehicles (UAVs) in support of operational and tactical requirements. This analysis evaluates the life cycle costs and combat efficiency of manned aircraft and UAVs currently in the DON research, development and procurement pipeline during the execution of an expanded end-to-end kill chain in a fast attack craft (FAC)/fast inshore attack craft (FIAC) anti-surface warfare (ASUW) mission. The results obtained provide insight into the operational benefits, anticipated fiscal costs and efficiency of UAVs operated independently or in concert with manned aircraft.

B. BACKGROUND

1. UAV Employment and Benefits

Employment of UAVs has become an integral part of the Department of Defense (DOD) military operation (Department of Defense, "Unmanned Systems Integrated Roadmap" 4). Within the DON, UAVs are currently or projected to perform intelligence, surveillance, reconnaissance and targeting (ISR&T), anti-submarine (ASW), mine counter measure (MCM), and ASUW operations in either conjunction or independent of manned aircraft.

The expanded role of UAVs has prompted significant development and procurement. As depicted in Table 1, from fiscal year (FY) 2016 to FY21 the DON projects the procurement of 53 UAVs representing an eight percent growth in UAV inventory (Department of the Defense, "Highlights of the DON FY2017 Budget" 4–5) and an associated 245% increase in funding from 200 million dollars ($M) in FY15 to

691 $M in FY17 (Department of Defense, “DOD: FY2017 President’s Budget Submission, Feb 2016: Navy Justification Book Vol 1 of 4. Aircraft Procurement” 199). During the same time period, manned aircraft with similar mission sets have a projected procurement of 230 aircraft representing a one percent increase in inventory (Department of the Defense, “Highlights of the DON FY2017 Budget” 4–5) and an associated 15.6% decrease in funding from 10,607 $M in FY15 to 8,947 $M in FY17 (Department of Defense, “DOD: FY2017 President’s Budget Submission, Feb 2016: Navy Justification Book Vol 1 of 4. Aircraft Procurement” 124).

Table 1. Department of Navy FY16-21 Aircraft Procurement. Source: Department of Defense, “DOD: FY2017 President’s Budget Submission, Feb 2016: Navy Justification Book Vol 1 of 4. Aircraft Procurement” 125).

Fixed Wing	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	FYDP
F-35B (STOVL JSF)	15	16	20	20	20	21	97
F-35C (CV JSF)	6	4	6	12	18	24	64
F/A-18E/F	5	2	14	-	-	-	16
EA-18G	10	-	-	-	-	-	-
E-2D AHE	5	6	5	3	4	5	23
P-8A (MMA)	17	11	6	13	-	-	30
UC-12W (USMC)	1	-	-	-	-	-	-
KC-130J (USMC)	2	2	2	2	2	2	10
Rotary Wing							
AH-1Z/UH-1Y	29	24	27	27	0	0	78
CH-53K (HLR)	-	2	4	7	13	14	40
VH-92A	-	-	-	6	6	5	17
MV-22B	19	16	6	6	6	14	48
MH-60R	29	-	-	-	-	-	-
UAV							
MQ-8C Firescout	5	1	2	2	2	2	9
RQ-21A Blackjack (APN/PMC)	6	8	4	5	5	3	25
MQ-4C Triton	4	2	3	3	5	6	19
Total Major Aircraft Programs	**153**	**94**	**99**	**106**	**81**	**96**	**476**

a. Benefits of UAVs

This investment in UAVs is driven by three benefits achieved by unmanned systems: “persistence, versatility and reduced risk to human life” (Department of Defense, “Unmanned Systems Integrated Roadmap” 20).

(1) Risk Reduction

UAVs eliminate the requirement to collocate a human operator and the air vehicle creating a viable option for high-risk flight operations (e.g., chemical, biological, radiological defense (CBRD), anti-access area denial (A2/AD) environments) via vehicle automation. Autonomy involves a capability (or a set of capabilities) that enables a particular action of a system to be automatic (Department of Defense Defense Science Board 1). Levels of automation vary across UAVs, from remote piloted vehicles (RPVs) to fully autonomous vehicles providing the capability to perform functions that include automated take-off and landing, execution of programmed flight plans and utilization on onboard sensors. Automation eliminates the requirement for an onboard human operator yet retains the human "in the loop" to perform supervisory functions or operations that by design are removed from the automated functionality. Via automation, the risk to human operators is removed.

(2) Persistence

With the removal of human operators, UAVs are able to reduce vehicle gross weight by replacing life support and cockpit components with smaller and lighter communication, navigation, and control systems (Scharre 14). This weight reduction results in a proportional decrease in required thrust and engine performance further reducing the gross weight of UAVs in comparison to manned aircraft. This weight reduction directly translates into increased flight duration and reduced refueling requirements.

(3) Versatility

Through the inclusion of open architecture, UAVs achieve increased versatility. Open architecture achieves two key advantages; modular design and standardized component interfaces (United States Government Accountability Office 6). Modular design enables UAVs to achieve payload versatility. Sensor packages can be selected and installed based on environment conditions, maximizing performance. These sensor swaps can be accomplished within hours enabling tactical flexibility. Similar modularization of weapons payloads will increase the mission flexibility of UAVs. Additionally, open architecture provides standardized component interfaces, which increase commonality between power, data and physical systems. Through open architecture, UAV mission flexibility is increased and the cost and duration of maintenance for system upgrades are reduced. The scope of this benefit is significantly greater for UAVs versus manned aircraft due to the lack of life support and in-aircraft control and display requirements necessary for manned aircraft, which limit modularity and interface standardization.

b. Studied Aircraft Overview

Based on current concepts of operation (CONOPS) and DON procurement and development status, three aircraft are included in this study for analysis. (Chapter II provides additional aircraft detail.)

(1) MH-60S Knighthawk–The MH-60S Knighthawk is a multi-mission combat manned helicopter supporting ASUW and MCM warfare. It deploys aboard air-capable and aviation surface ships (Department of the Navy, "Naval Aviation Vision 2016–2025" 62).

(2) MQ-8C Fire Scout–The MQ-8 Fire Scout is an unmanned UAV employed as an organic ISR, ASUW and MCM asset. It is designed to operate from suitably equipped air-capable ships (Department of the Navy, "Naval Aviation Vision 2016–2025" 63).

(3) RQ-21A Blackjack–The RQ-21A Blackjack is a tactical multi-intelligence unmanned aerial system (UAS) that will support Marine Corps operations, and eventually Navy operations, including expeditionary units and regiments, U.S. Naval Expeditionary Combat Command, L-Class (amphibious) ships and Naval Special Warfare customers (Department of the Navy, "Naval Aviation Vision 2016–2025" 29).

2. Kill Chains

Naval aviation uses the term "kill chains" to describe the operational sequence of events that must occur to destroy a target: "Find-Fix-Track-Target-Engage-Assess" (F2T2EA) (Department of the Navy, "Naval Aviation Vision 2016–2025" 14–15).

a. Kill Chain Events

- Find—the detection of a contact of military interest
- Fix—determination of the location of the detected contact

- Track—the ability to maintain precise and continuous contact location
- Target—selection of an appropriate weapon for use against a contact
- Engage—the authorized employment of selected weapon against a designated contact
- Assess—determination of weapon engagement effectiveness

b. Kill Chain Execution

Kill chains sequences can be platform focused or integrated, as depicted in Figure 1. Platform focused kill chains are executed end-to-end by an individual platform such as an aircraft, submarine or surface ship. Integrated kill chains are executed by multiple platforms within a single kill chain; for example, one aircraft provides target detection and targeting while a surface ship delivers the weapon and a second aircraft performs post-engagement assessment.

While the sequence of events within a kill chain is "platform agnostic," the platform to event pairing in integrated kill chains is dependent on multiple factors which influence the effectiveness and kill chain speed of execution to include; platform sensor capabilities, command and control network availability and platform on-board ordnance. The effectiveness of integrated kill chain execution by manned and unmanned platforms is also influenced by command and control authority location. For manned aircraft, the command and control authority is co-located aboard the platform. Conversely, for unmanned platforms the command and control authority is remotely located. This difference in command and control authority location effects the time and communications requirements necessary to execute and progress through the kill chain sequence, potentially negatively affecting the time required to execute an end-to-end kill chain.

Figure 1. NAVAIR Kill Chains. Source: Department of the Navy, "Naval Aviation Vision 2016–2025" (14-15).

C. MOTIVATION

The increase in DON UAV investment and procurement requires the development and testing of new or modified Concepts of Operation (CONOPS) to evaluate platform focused and integrated kill chain execution effectiveness. Current CONOPS for the UAVs studied incorporate the pairing of unmanned Fire Scout aircraft and MH-60S manned helicopters in the execution of ISR&T, ASUW and ASW operations (Martin 21). The Fire Scout's extended flight endurance and payloads enable a significant increase in the warfighter's maritime domain awareness (MDA) and allow a complementary pairing with the sensors and weapons payloads carried by MH-60S in the execution of precision ASUW.

Unlike Fire Scout and MH-60S, the Blackjack has yet to be approved for full rate production (FRP) and lacks operational deployments or tested CONOPS. Currently the Blackjack is envisioned as an ISR&T multiplier for United States Marine Corps (USMC) forces deployed aboard amphibious assault ships and ashore. Blackjack UAVs are currently projected to operate independently or in a flight of two, with one aircraft conducting a passive mission (target detection) and one aircraft conducting an active mission (tracking and targeting) (Department of the Navy, "Performance Based

Specification Version 1.6 for STUAS/Tier II UAS" 12). The addition of Fire Scout and Blackjack to the DON inventory creates an opportunity to greatly expand the DON ability to conduct ISR&T in contested or A2/AD environments and with the future inclusion of onboard ordnance a new platform to fully execute ASUW kill chains.

Under increased DOD budgetary pressure, the return on investment (ROI) of the Fire Scout and Blackjack UAV programs increased flight endurance and sensor/ordnance payloads will be determined by their ability to effectively increase the warfighter's achievable combat power through the successful execution of operational missions. Despite this need for cost-wise validation of the Fire Scout and Blackjack programs, the current methodology utilized to simulate and evaluate kill chain success or contributions lacks the key metric of cost and excludes the contributions generated through multiple kill chain executions per sortie (Dunaway 61). This thesis, through analytical and simulation analysis will answer the following questions:

- What is an effective UAV and manned aircraft deployment force structure in order to achieve operational FAC / FIAC ASUW mission requirements?
- Given fixed operational requirements, do Fire Scout and Blackjack UAVs provide a cost effective alternative to manned aircraft when operated in a contested ASUW environment?
- What is the added value of Fire Scout and Blackjack UAVs in the execution of expanded end-to-end ASUW kill chains?

D. DEFINITIONS AND FOCUS

1. Definition

a. Expanded Kill Chain

This thesis shall specifically address an "expanded kill chain." The expanded kill chain builds upon the conventional F2T2EA kill chain sequence of events by including flight deck positioning, takeoff, recovery, mechanical failure rates, mishap rates and post flight maintenance activities.

b. Cost Elements

For the purpose of this thesis, expanded kill chains for aircraft and UAVs shall be evaluated for efficiency by determining cost per kill executed. Considered cost elements shall be composed of the following:

(1) Average Procurement Unit Cost (APUC):

Calculated by dividing total procurement cost by the number of items to be procured. "Total procurement cost includes flyaway, rollaway, sail away cost (that is, recurring and nonrecurring costs associated with production of an item such as hardware/software, Systems Engineering (SE), engineering changes and warranties), plus the costs of procuring Technical Data (TD), training, support equipment, and initial spares" (Hagan B-21). In this study, aircraft loss due to enemy fire and catastrophic mishaps results in a replacement cost based on the aircraft type-dependent APUC.

(2) Operating and Support Cost (O&S):

"A life cycle cost (LCC) cost category that includes all personnel, equipment, supplies, software, and services, including contract support, associated with operating, modifying, maintaining, supplying, training, and supporting a defense acquisition program in the DOD inventory" (Hagan B-178).

(3) Ordnance Cost:

The cost per round of expended ordnance.

2. Focus

The focus of this study is the cost-wise efficiency of the UAVs and manned aircraft in the execution of expanded kill chains. The purpose is to determine an efficient composition of manned and unmanned aircraft to minimize cost per kill.

E. SCOPE, LIMITATIONS AND ASSUMPTIONS

The UAVs and manned aircraft studied are capable of executing various mission sets to include ASUW, ASW, MCM and ISR&T. Additionally, all aviation platforms studied utilize multiple sensors, which provide flexibility and effectiveness across multiple spectrums and target categories. Simulation and analysis across all possible payload configurations, spectrums, and threat environments requires operational, maintenance and performance data that is either unavailable or beyond the classification of this thesis. This breadth of variables in conjunction with the continued technological development of UAVs, prohibits a definitive “solution” across all potential variables and scenarios.

In order to achieve quantifiable and tangible results, this study limits its analysis to the case of the described models of UAVs and manned aircraft in the execution of contested maritime anti-surface warfare operations occurring in a daylight-operating environment as further detailed in Chapter II. The results of this analysis provide a method to compare the selected performance metrics across multiple aviation platforms and in varying deployment configurations based on fixed operational requirements.

This study’s analysis is influenced by its underlying assumptions. These assumptions can be classified as pertaining to the studied UAVs and aircraft, costing, the simulated enemy (RED) forces and scenario development.

1. Studied UAV and Manned Aircraft Assumptions

- Airframe performance characteristics utilized will closely mirror those currently available.
- Sensor performance characteristics mirror those currently available or approximations are developed through intermediate calculations.
- Aircraft and UAVs are limited to use of electro-optical (EO) sensors.
- Weapons carrying and delivery capabilities reflect currently employed or projected capabilities.
- Aircraft and UAVs are deployed and operated in the quantity and configuration detailed in existing CONOPS or in notional configurations for the purpose of sensitivity analysis and analysis of alternatives.
- Aircraft and UAV maintenance periods, failure rates and mishap rates are based on currently available data or of aircraft/UAVs within the DOD that hold similar physical and performance characteristics.

2. Costing Assumption

- All aircraft, UAV and ordnance costs are based on a FY16 baseline.
- Manpower and training costs are sunk costs and not included in the analysis
- BLUE surface ships procurement and operating costs are sunk costs and not included in the analysis.

3. Simulated Enemy Assumptions

- RED forces possess no ASUW capabilities and are unable to either hold at risk or decrement the effectiveness of BLUE surface ships.
- RED force levels are notional and not based on any existing or projected deployment of any known naval forces.
- RED maritime forces are limited to patrol craft and coastal patrol boats with short-range surface to air missile (SAM) capabilities.
- RED forces are limited to visual detection.

4. Scenario Development Assumptions

- All simulated events occur in a strictly overwater operating environment.
- All BLUE aircraft flight operations are simulated to occur in a daylight-operating environment.
- BLUE forces maintain air superiority within the simulated operating environment.
- Communication and GPS capabilities are continuously maintained in all simulations and analysis.
- Common Control Station (CCS) technology enables interoperability of specified quantities and types of manned and unmanned aircraft.
- RED forces have no fixed tactical deployment.
- RED forces have no assumed employment tactics.
- BLUE aircraft and UAV interoperability exists.
- BLUE aircraft achieve 100% accurate classification of RED and neutral contacts

F. LITERATURE REVIEW

This thesis is a convergence of the fields of operations research and cost estimation. Operations research is primarily lead by the academic and research work performed by the United States military, academic institutions and U.S. government contracted industries. The field of operations research provides the fundamental constructs and theory behind the analytical and simulation analysis performed in this study. The development, derivation and calculation of this study's measures of performance and modeling design are based on the principles of operations research. Cost-estimation research and discussion in the field of cost estimation is led by academic institutions and the Government Accountability Office (GAO). This field guides the methodology that enables the development of the fiscal constraints and resources implicit in the operation of the studied UAVs and manned aircraft. While no previous work fully examines the cost effectiveness of kill chains, we provide a brief description of influential previous academic and academic work in the relevant fields in the proceeding paragraphs.

1. Operations Research

Brickner (30-35) provided an analysis of time critical target kill chains with simulation and modeling. Extrapolating and building on the model developed by U.S. Navy Naval Air Systems Command (NAVAIR), Brickner explored and evaluated the effects of system performance and varying CONOPS to validate and provide recommendations on the NAVAIR fielded model. The analysis performed by Brickner investigates the efficiency and performance of traditional F2T2EA kill chains but does not take into the additional events (examples included maintenance and failure rate) contained within the expanded kill chain discussed within this study.

Lee (52-68) studied the concept of kill chain execution by joint manned and unmanned vehicles. Using simulation models Lee examined the time efficiencies of the manned-unmanned concept. The analysis provided insights into methods to improve efficiency through proposed technological developments and modifications to concepts of operation. Lee's kill chain analysis provides extensive investigation into command and control and network requirements that are not included within this study.

Bloye (18-50) studied the effect of networks on mission effectiveness. The analysis centered on the performance metric of time-to-kill and the development of a kill chain assessment tool. The assessment tool developed and evaluated a methodology to optimize systems of available resources in time-sensitive targeting scenarios. Similar to Brickner's study, Bloye's study of kill chain analysis does not take into account the additional events included in this study's expanded kill chain.

2. Cost Estimation

Godshaw (87-92) performed a cost-effective analysis of unmanned aerial vehicles and satellite systems. Focusing on the procurement, availability and capabilities of multiple UAV and satellite systems, the study developed recommendations to optimize the cost effectiveness of unmanned systems in the performance of surveillance and reconnaissance. While comprehensive in the field of cost analysis, Godshaw's study does not incorporate the dynamic and statistical impact of the kill chain events utilized in this study.

Yilmaz (28-35) conducted a study on the cost effectiveness of UAVs. Examining procurement and operational costs, the research conducted on analysis of alternatives in the performance of border security.

G. THESIS FLOW

Chapter II discusses scenario development. It also establishes measurement of performance, methodology, utilized data sets and sources. Chapter III describes the implementation of an object model paradigm simulation package, SIMIO to perform continuous analytical analysis of the extended kill chain. Chapter IV presents the initial simulation results. Chapter V investigates model sensitivity and presents an analysis of alternatives. Chapter VI provides conclusion and recommendations.

II. SCENARIO DEVELOPMENT AND SOURCES

A. OVERVIEW

This chapter provides background for the scenario development and modeling used to evaluate the effectiveness of multiple combinations of manned and unmanned aerial vehicles within the USN research, testing, development and evaluation (RTD&E), and procurement process or in current operational use. It describes the models of aircraft systems to be evaluated, defines the study's measures of effectiveness (MOE) and measures of performance (MOP), and details the operational scenario and concepts of operational employment.

B. EVALUATED AIRCRAFT PROGRAMS

The following section presents the three aircraft that are analyzed within this study. Along with general descriptions of the aircraft and their associated primary mission sets, we present aircraft, sensor and ordnance performance and cost data utilized within the study.

1. MQ-8 Fire Scout

The MQ-8 Fire Scout (Figure 2) is a vertical takeoff and landing tactical unmanned aerial vehicle designed to operate from equipped air-capable ships (Department of Defense, "Naval Aviation Vision 2016–2025" 63) and is manufactured by Northrop Grumman.

Figure 2. MQ-8C Fire Scout. Source: Northrop Grumman (par. 1).

The Fire Scout unmanned aerial system (UAS) includes air vehicles, sensor packages, a tactical data link and mission control system. It is capable of automated take-offs and landings and executing programmed flight patterns. Current sensor packages include electro-optical/infrared (EO/IR) and laser designation capabilities. Future modifications of the Fire Scout plan incorporate Advanced Precise Kill Weapons System II (APKWS II), Coastal Battlefield Reconnaissance and Analysis (COBRA) mine detection system and maritime radar sensors. With a range of 150 nautical miles and flight endurance of 12 hours, these sensor and ordnance payloads will allow Fire Scout to perform ISR&T, ASUW, ASW, and MCM mission in support of combatant commanders (MQ-8C Fire Scout Data Sheet 1).

Fire Scout received approval for low rate initial production (LRIP) in 2007, Full Rate Production (FRP) in 2009 and projected procurement is nine Fire Scout UAS by 2021 (Department of Defense, “Selected Acquisition Report: MQ-8 Fire Scout” 9). The Fire Scout UAS average unit procurement cost (APUC) is 28.261 $M FY16 (Volpe 1).

a. Vehicle, Sensor and Ordnance Specifications

Table 2 provides a summary of the MQ-8C vehicle, sensor and ordnance performance specifications. NAVAIR, program executive office (PEO) unmanned aviation and strike weapons (U&W) provided aircraft performance data (Wolt 1-5). We obtained sensor data from FLIR Systems Incorporated (FLIR.com) and ordnance performance data from Jane's Air Launched Weapons (janes.ihs.com). Table 2 annotates performance parameters determined through intermediated calculations as "Calculated" for the data source and "Notional" for all notional values. The calculations appear in Appendix A.

Table 2. MQ-8C Aircraft, Sensor and Ordnance Performance

				Source
Air Vehicle	**MQ-8**	**Endurance (hrs)**	12	Wolt
		Range (nm)	150	Wolt
		Max/Loiter Speed (kcas)	130/60	Wolt
		Ceiling (ft MSL)	17,000	Wolt
Sensor	**FLIR Brite-Star II**	**EO Sensor Sweepwidth (m)**	During Aircraft Surveillance Operations– 940.0	Calculated
		Laser Designation Range (nm)	5	Notional
Ordnance	**APKWS II (planned)**	**Maximum Range (m)**	5000	Jane's
		CEP (m)	2	Jane's
		Maximum Payload (quantity)	7	Notional

b. Vehicle Maintenance and Reliability

Table 3 presents MQ-8C maintenance data. NAVAIR, program manager air (PMA) 266, Fire Scout Mission Systems Assistant Deputy Program Manager provided mean time between failure (MTBF) and mean time to repair (MTTR) data (Rioux 13). Helicopter Sea Combat Wing Pacific (HSCWINGPAC) (Martin 26) provided scheduled maintenance interval and duration data. We calculate planned maintenance interval durations based on mean duration of anticipated hourly and daily maintenance requirements.

Table 3. MQ-8 Maintenance and Reliability Data

				Source
Air Vehicle	**MQ-8C**	**MTBF (hrs)**	30	Rioux
		MTTR (hrs)	2.5	Rioux
		Planned Maintenance Interval (hrs)	25	Martin
		Planned Maintenance Duration (Ave) (hrs)	1.6	Martin

c. Vehicle Mishap Rates

Naval Safety Center provided MQ-8 mishap rates, as of 15 March 2016. Based on cumulative data collected from FY10 to FY16, the MQ-8 catastrophic mishap rate is 53.3 mishaps per 100,000 flight hours (Perry 2).

d. Vehicle and Ordnance Cost Data

NAVAIR, PEO (U&W) 4.2, provided MQ-8 vehicle cost data (Volpe 2). The DOD FY17 President's Budget, Navy Weapons Book (Department of Defense 131–135) provided HELLFIRE cost data and the DOD FY17 President's Budget, Navy Ammunition Book (Department of Defense, "Department of Defense FY2017 President's Budget. Navy Ammunition Book" 110–115) provided APKWS-II cost data. Table 4 presents APUC, ordnance and derived cost per flight hour data for the MQ-8. Operating cost per flight hour calculation is based on NAVAIR provided budgeted O&S costs and annual flight hour projections (Volpe 2). Chapter IV details cost per flight hour methodology and Appendix B contains sample calculations.

Table 4. MQ-8C Aircraft and Ordnance Cost Data

				Source
Air Vehicle	**MQ-8**	**APUC (per vehicle) (FY16 $M)**	27.48	Volpe
		Cost per Flight Hour (FY16 $M)	0.02	Calculated
Ordnance	**HELLFIRE (planned)**	**APUC (per round) (FY16 $M)**	0.08	DOD
	APKWS II (planned)	**APUC (per round) (FY16 $M)**	0.03	DOD

2. RQ-21 Blackjack

The RQ-21 Blackjack (Figure 3) is a twin tailed, fixed wing small tactical unmanned aircraft system (STUAS) designed to provide tactical ISR capability for amphibious assault ships manufactured by Boeing/Insitu Incorporated. The Blackjack UAS consists of five aircraft, a control station, launch and recovery equipment, tactical data links, multi-mission payloads and support equipment. It is capable of performing shipboard take-offs and recoveries. Current sensor packages include EO/IR, and a laser rangefinder/designator. Future payloads are projected to provide laser designation capabilities. With cruising speeds of 80 nautical miles per hour and a flight endurance of ten hours, the Blackjack is designed to provide persistent maritime and overland ISR&T capabilities (Department of the Navy, “Naval Aviation Vision 2016–2025” 29).

LRIP approval for Blackjack occurred in 2013 and FRP approval is anticipated in 2016. Blackjack projected procurement is 37 Blackjack UAS through FY21 (Volpe 3). Blackjack APUC per vehicle is 4.470 $M FY16 (Volpe 3).

Figure 3. RQ-21 Blackjack. Source: United States Navy (par. 3)

a. *Vehicle and Sensor Specifications*

NAVAIR, PEO (U&W) provided RQ-21 performance specifications (Wolt 1-5). We reference Hoodtech Incorporated (hoodtechvision.com), the Office of the Director, Operational Test and Evaluation (DOT&E) reports for the RQ-21 (Department of Defense, “FY15 Navy Programs: RQ-21A Blackjack UAS” 1–5) and the DON, PEO (U&W) Performance Based Specifications for STUAS (Department of the Navy, “PBS Version 1.6 for STUAS/Tier II UAS” 15–20) for sensor specifications. Appendix A presents sensor performance values calculations. Table 5 presents performance data and applicable sources. “Calculated” annotates performance parameters determined through intermediated calculations and “Notional” annotates all notional values.

Table 5. RQ-21 Aircraft and Sensor Performance

				Source
Air Vehicle	**RQ-21**	**Endurance (hrs)**	10	Wolt
		Range (nm)	50	Wolt
		Max/Loiter Speed (kcas)	80/55	Wolt
		Ceiling (ft) MSL	15,000	Wolt
Sensor	**Hoodtech Alticam AC-10**	**EO Sensor Sweepwidth (m)**	During Aircraft Surveillance Operations – 1203.2	Calculated
		Laser Designation Range (nm)	0.7	DON

b. Vehicle Maintenance and reliability

The study uses established DOT&E (Department of Defense, "FY15 Navy Programs: RQ-21A Blackjack UAS" 3) and PEO U&W (Department of the Navy, "PBS Version 1.6 for STUAS/Tier II UAS" 80–83) key performance parameters for RQ-21 maintenance and reliability statistics. Table 6 summarizes the maintenance and reliability data used in modeling the RQ-21.

Table 6. RQ-21 Maintenance and Reliability Data

				Source
Air Vehicle	**RQ-21**	**MTBF (hrs)**	45	DON
		MTTR (hrs)	0.5	Notional
		Planned Maintenance Interval (hrs)	100	DOD
		Planned Maintenance Duration (Ave) (hrs)	3.5	DOD

c. Vehicle Mishap Rates

The key performance parameter for the RQ-21 mishap rate is one mishap per 1000 flight hours (Department of the Navy, "PBS Version 1.6 for STUAS/Tier II UAS" 3).

d. Vehicle Cost Data

NAVAIR, PEO (U&W) 4.2 provided RQ-21 cost data (Volpe 3). Table 7 presents RQ-21 APUC and derived cost per flight hour data. Operating cost per flight hour calculation is based on NAVAIR, PEO (U&W) 4.2 provided budgeted O&S costs and annual flight hour projections (Volpe 3). Chapter IV details cost-per-flight-hour methodology, and Appendix B contains sample calculations.

Table 7. RQ-21 Aircraft Cost Data

				Source
Air Vehicle	**RQ-21**	**APUC (per vehicle) (FY16 $M)**	4.33	Volpe
		Cost per Flight Hour (FY16 $M)	0.01	Calculated

3. MH-60S

The MH-60S (Figure 4) is a multi-mission combat helicopter designed to provide surface warfare, anti-submarine warfare, mine countermeasures, combat search and rescue and logistics capabilities to aircraft carriers, amphibious assault ships and air capable surface ships. Current sensors and payloads include EO/IR sensors, HELLFIRE missiles, a 20 millimeter fixed forward firing gun and crew served weapons. Future payloads include an airborne laser mine detection and neutralization system and APKWS-II. With a cruise speed of 75 nautical miles per hour, flight endurance of three and a half hours and current payloads the MH-60S is capable of executing ISR&T and ASUW missions (Department of the Navy, “Naval Aviation Vision 2016–2025” 62). MH-60S LRIP occurred in 1998, FRP in 2002 and DON procurement completion occurred in 2015 with the purchase of 275 helicopters (Department of Defense, “SAR: MH-60S Fleet Combat Support Helicopter” 8).

Figure 4. MH-60S Knighthawk. Source: Sikorsky (par. 1).

a. Aircraft, Sensor and Ordnance Specifications

Table 8 provides a summary of the MH-60S aircraft, sensor and ordnance parameters used in the study. The study references NAVAIR (Naval Air Systems Command 1) for aircraft performance specifications. The Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (Weatherington 12-15) provided information regarding sensor specifications. We obtain ordnance performance data from Jane's Air-Launched Weapons (janes.ihs.com), Defensetech.com (McGarry par. 4) and Predator: The Secret Origins of the Drone Revolution (Whittle 195). Table 8 annotates performance parameters determined through intermediate calculations as "Calculated" for the data source and "Notional" for all notional values. Appendix A provides sample calculations.

Table 8. MH-60S Aircraft, Sensor and Ordnance Performance

				Source
Aircraft	**MH-60S**	**Endurance (hrs)**	3.5	NAVAIR
		Range (nm)	245	NAVAIR
		Max/Loiter Speed (kcas)	180/75	NAVAIR
		Ceiling (ft) MSL	13,000	NAVAIR
Sensor	**Raytheon MTS-A AAS-44C(V)1**	**EO Sensor Sweepwidth (m)**	Detection – 1203.2	Calculated
		Laser Designation Range (nm)	5	Whittle
Ordnance	**HELLFIRE**	**Maximum Range (m)**	8000	Jane’s
		CEP (m)	5	Notional
		Maximum Payload (quantity)	8	Jane’s
	APKWS II (planned)	**Maximum Range (m)**	5000	Jane’s
		CEP (m)	2	Jane’s
		Maximum Payload	19	McGarry

b. Aircraft Maintenance and Reliability

The study uses key performance parameters obtained from DOD Selected Acquisition Reports (SAR) (Department of Defense, “SAR: MH-60S Fleet Combat Support Helicopter” 6) and HSCWINGPAC provided historical data (Martin 26) for maintenance and reliability statistics. We calculate planned maintenance interval durations based on mean duration of anticipated hourly and daily maintenance requirements. Table 9 presents the maintenance and reliability data modeled for the MH-60S.

Table 9. MH-60S Maintenance and Reliability Data

				Source
Aircraft	**MH-60S**	**MTBF (hrs)**	20.3	DOD
		MTTR (hrs)	3.6	DOD
		Planned Maintenance Interval (hrs)	30	Martin
		Planned Maintenance Duration (Ave) (hrs)	10.7	Calculated

c. Vehicle Mishap Rates

The Naval Safety Center provided MH-60S mishap rates, as of 15 March 2016 (Perry 2). Based on a historical average from FY00 to FY16, the MH-60S catastrophic mishap rate is 1.33 catastrophic mishaps per 100,000 flight hours.

d. Vehicle Cost Data

The MH-60S DOD SAR (Department of Defense, "SAR: MH-60S Fleet Combat Support Helicopter" 7) provided MH-60S aircraft cost data. The DOD FY17 President's Budget, Navy Weapons Book (Department of Defense, "DOD FY2017: President's Budget. Navy Weapons Book" 131–135) provided HELLFIRE cost data and the DOD FY17 President's Budget, Navy Ammunition Book (Department of Defense, "DOD FY2017: President's Budget. Navy Ammunition Book" 110–115) provided APKWS-II cost data. Table 10 presents APUC, ordnance and derived cost per flight hour data for the MH-60S. Operating cost per flight hour calculation is based on the MH-60S DOD SAR budgeted O&S costs and annual flight hour projections. Chapter IV details cost per flight hour methodology and Appendix B contains sample calculations.

Table 10. MH-60S Aircraft and Ordnance Cost Data

				Source
Aircraft	**MH-60**	**APUC (per aircraft) (FY16 $M)**	28.46	DOD
		Cost per Flight Hour (FY16 $M)	0.02	Calculated
Ordnance	**HELLFIRE (planned)**	**APUC (per round) (FY16 $M)**	0.08	DOD
	APKWS II (planned)	**APUC (per round) (FY16 $M)**	0.03	DOD

C. SCENARIO DEVELOPMENT

In order to evaluate the performance and cost efficiency of the UAVs and manned aircraft within this study, the scenario underlying the analysis and simulation is structured to represent currently projected tactical situations and asset utilization. According to the United States Joint Sea Services, the ability to gain and maintain sea control is one of the essential functions to defeat aggression and protect the maritime commons (Department of the Defense, “A Cooperative Strategy for 21st Century Seapower” 22–26). Surface warfare via integrated kinetic fires enables the destruction of enemy naval forces, resulting in the establishment of local maritime superiority. As such this study focuses on a simulated anti-surface warfare campaign and provides operational and programmatic planners with a tool to determine the effectiveness of various combinations of manned and unmanned aircraft in the execution of the kill chain for enemy naval surface threats.

For the purpose of this study, we utilize a non-geographic specific area of operations (AO) to represent the projected operational use of UAVs and manned aircraft within a maritime mission environment. The description below provides a brief description of the measures of effectiveness (MOE), measures of performance (MOP), scenario operational environment, initial conditions, operating conditions, and concept of operation that we use in the analysis contained in subsequent chapters.

1. Measures of Effectiveness (MOE)

The MOEs developed and evaluated by this study pertain to the advantage of various combinations of manned and unmanned aerial vehicles in the execution of a surface warfare kill chain. The MOEs are

- Mean detection time
- Mean time to 50% attrition of hostile naval vessels
- Number of hostile forces killed per campaign.

The time to detection and classification of hostile naval forces and the time to destruction of hostile (RED) naval vessels directly affects the survivability of BLUE forces and the expenditure of resources required to fully develop the BLUE force maritime domain awareness (MDA). Through the minimization of the duration of these events, expedient identification and separation of RED from neutral forces (commercial shipping and maritime traffic) is achieved and enables the subsequent targeting and destruction of RED forces. Additionally, through the minimization of time to RED classification, the BLUE common operating picture (COP) develops more rapidly enabling the improved allocation of BLUE resources. Minimized time to detection, classification and destruction of RED forces achieves improved attrition of RED forces, preservation of BLUE forces and improved BLUE force combat power.

Through determination of the mean time until 50 percent attrition of RED forces, the study compares and evaluates the combat effectiveness of multiple manned and unmanned aircraft combinations. The study selects 50 percent as a measurement for when RED forces no longer retain combat effectiveness (Kline par. 2). By observing the number of RED detections and destructions over the length of a campaign, the study evaluates the effect of aircraft availability on FAC / FIAC ASUW kill chains for various combinations of manned and unmanned aerial vehicles. Aircraft availability is influenced by maintenance requirements, aircraft loss to hostile fire and loss to catastrophic failure.

The study evaluates the aircraft over the duration of a campaign to ensure the probabilistic rate of occurrence of these events is adequately captured. Chapter III presents the methodology and derivation of the MOEs.

2. Measures of Performance (MOP)

The MOP developed and evaluated during this study pertains to the cost-wise advantage of various combinations of manned and unmanned aerial vehicles in the execution of a surface warfare kill chain. The evaluated MOP is

- Cost per hostile kill

Cost per RED kill is evaluated over the length of a campaign to provide operational and programmatic planners with insight into the projected cost and relative fiscal savings or expenses that result from various combinations of manned and unmanned systems. Chapter IV provides the methodology and derivation of the MOP.

3. Anti-Surface Warfare (ASUW) Scenario

The scenario presented is representative of potential naval conflicts and subsequent combat operations while not directly associated with any specific geographic location or adversary.

a. Background and Initial Conditions

The AO is characterized as a regional conflict in which BLUE naval forces support the enforcement of ally nation territorial waters. BLUE naval forces include a surface action group (SAG) composed of two strike capable surface combatants (guided missile cruiser (CG) / guided missile destroyer (DDG)) and one amphibious ship (littoral combat ship (LCS) / amphibious transport dock (LPD) / landing ship dock (LSD)). RED naval forces include coastal patrol boats and fast attack craft. RED forces contain no aviation assets.

The U.S. mission is to establish maritime supremacy and defeat RED naval forces within the AO. The mission for all available BLUE aviation assets is the detection, tracking and classification of all RED naval forces within the AO. If able, BLUE aviation assets are additionally tasked with the destruction or provision of targeting data for additional BLUE asset prosecution of all RED naval forces.

b. Operating Conditions

In order to reduce the number of variables in the model, aircraft are limited to EO sensors. The study further controls sensor performance variability by restricting the model's operating environment to day only over-water operations with negligible cloud cover. The maritime environment consists of open-ocean and littoral waters. Variable volumes of neutral shipping are present within the AO. The study's modeled AO is a non-permissive environment.

c. BLUE Forces

All BLUE aviation assets are based and operated from BLUE air capable ships. BLUE aviation assets quantities in the presented CONOPS are "upon-deployment" numbers suffer attrition from RED fires and catastrophic mishaps and are non-replenishable within the simulated campaign. BLUE air-capable ships are the takeoff, recovery, refueling and rearmament locations for all BLUE aviation assets. For the simulation, BLUE air-capable ships have unlimited aviation ordnance and fuel stores and do not suffer attrition.

d. RED Forces

RED force distribution is randomized throughout the designed AO. RED naval forces have no predetermined tactics and the study does not incorporate RED force coordination in the model. RED naval forces suffer attrition from BLUE aviation asset fires. Table 11 references Jane's Fighting Ships (janes.ihs.com) for RED naval forces performance characteristics and capabilities based on values for similar platforms.

Table 11. RED Naval Forces and Ordnance Performance Data

				Source
Ship Type	**Fast Attack Craft / Patrol Craft**	**Length (m)**	42.6	Jane's
		Beam (m)	12.2	Jane's
		Speed (kts)	40	Jane's
Weapons	**SAM**	**Max Range (m)**	4200	Jane's
		Max Altitude (m)	2300	Jane's
		CEP (m)	1.5	Jane's
		Guidance	Optically sighted Passive IR seeker	Jane's

e. Concepts of Operation (CONOPS)

Within this study, the selection of unclassified CONOPS for evaluation is motivated by current HSCWINGPAC deployment configurations (Hock pars. 4-7) and proposed configurations based on potential technological growth and development.

(1) CONOPS 1: MH-60 and MQ-8 (HSCWINGPAC / Current)

MQ-8 and MH-60 aircraft conduct joint ASUW operations within the AO. MOEs and MOPs will be evaluated across a SAG embarked with 3 MQ-8 and three MH-60. MQ-8 and MH-60 aircraft are tasked with RED detection, classification and targeting. MH-60 aircraft are tasked with the prosecution of self-designated and MQ-8 designated targets via HELLFIRE missiles. Evaluation of CONOPS 1 also included a MH-60 only equipped SAG. Table 12 presents the CONOPS 1 aircraft tasks and SAG configurations.

Table 12. CONOPS 1—MH-60 and MQ-8

	MH-60 (quantity)	MQ-8 (quantity)	Tasks
CONOPS 1A	3	3	MQ-8: RED detection, classification and targeting MH-60: RED detection, classification, targeting and prosecution (via HELLFIRE)
CONOPS 1B MH-60 Only	6	0	MH-60: RED detection, classification, targeting and prosecution (via HELLFIRE)

(2) CONOPS 2: MH-60 and MQ-8 (Future)

MQ-8 and MH-60 aircraft conduct joint ASUW operations within the AO. CONOPS 2 includes the utilization of planned technological advances to include MH-60 APKWS II and MQ-8 employment of APKWS II weapon systems. Inclusion of this technology enables MQ-8 target prosecution. MQ-8 and MH-60 execute end-to-end FAC / FIAC ASUW kill chains. Table 13 presents the CONOPS 2 aircraft tasks and SAG configurations.

Table 13. CONOPS 2—MH-60 and MQ-8 (Future)

	MH-60 (quantity)	MQ-8 (quantity)	Tasks
CONOPS 2A	3	3	MQ-8: RED detection, classification, targeting and prosecution (via APKWS II) MH-60: RED detection, classification, targeting and prosecution (via APKWS II)
CONOPS 2B MH-60 only	6	0	MH-60: RED detection, classification, targeting and prosecution (via APKWS II)

(3) CONOPS 3: MH-60 and RQ-21 (Future)

Programmatically, the RQ-21’s projected utilization is as a United States Marine Corps (USMC) ground and sea based ISR&T asset. CONOPS 3 extends that utilization and incorporates the RQ-21 into the aviation assets available to the BLUE naval forces within the scenario. Modeled RQ-21s are equipped with planned sensor payloads to include laser designation capabilities. CONOPS 3 models MH-60 aircraft with APKWS II ordnance. RQ-21 and MH-60 aircraft perform RED detection, classification and targeting. MH-60 aircraft execute the prosecution of self-designated and RQ-21 designated targets. Table 14 presents the CONOPS 3 aircraft tasks and SAG configurations.

Table 14. CONOPS 3—MH-60 and RQ-21 (Future)

	MH-60 (quantity)	**RQ-21 (quantity)**	**Tasks**
CONOPS 3	4	6	RQ-21: RED detection, classification and targeting MH-60: RED detection, classification, targeting and prosecution (via APKWS II)

(4) CONOPS 4: MQ-8 and RQ-21 – Unmanned Only (Future)

CONOPS 4 evaluates an unmanned vehicle only SAG configuration. Modeled RQ-21s are equipped with planned sensor payloads to include laser designation capabilities. CONOPS 4 models MQ-8 with APKWS II ordnance. RQ-21 and MQ-8 aircraft perform RED detection, classification and targeting. MQ-8 aircraft execute the prosecution of self-designated and RQ-21 designated targets. Table 15 presents the CONOPS 4 aircraft tasks and SAG configurations.

Table 15. CONOPS 4—MH-60 and RQ-21 Unmanned Only (Future)

	MQ-8	**RQ-21 (quantity)**	**Tasks**
CONOPS 4	3	9	RQ-21: RED detection, classification and targeting MQ-8: RED detection, classification, targeting and prosecution (via APKWS II)

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III. METHODOLOGY

A. OVERVIEW

This chapter introduces the simulation model utilized in the study. The chapter contains an end-to-end description and explanation of the processes incorporated in the model and initial results.

B. SIMULATION AND MODELING

For this study, we select SIMIO, Simulation modeling framework based on intelligent object (Thiesing and Pegden 1–4), as the application to model, simulate and perform analysis of the expanded kill chain. SIMIO is a software application used in the Naval Postgraduate School Operations Research program and facilitates the modeling, simulation and analysis of dynamic systems. Benefits of SIMIO include the ability to incorporate multiple events and entity types within a single model, the application of discrete and continuous systems and the ability to rapidly process iterative simulations in support of statistical analysis.

1. SIMIO

In SIMIO, the base unit is an object. Objects in SIMIO represent machines, processes, and facilities. In this simulation, the primary objects of interest are manned aircraft, unmanned aerial vehicles and specific events (examples include maintenance, takeoff and surveillance). We construct a model to represent a real world system through the connection of these objects. In this study, the system represents an expanded FAC / FIAC ASUW kill chain.

In conjunction with its object-based orientation, SIMIO supports the development of a modeling environment containing processes, system dynamics and methods for post simulation analysis.

a. Properties and States

Properties control the behavior and actions of the object within the model. Examples are flight endurance, maximum velocity and scheduled maintenance interval. User created and defined properties allow high levels of model customization and fully developed object behaviors. A second method to define objects is through the use of state variables. Unlike properties, state variables change during the course of the simulation. Total flight time, ordnance payload, and altitude are examples of state values used in the study. Properties and states may be assigned to specific model objects or apply to the entire modeled system. In its entirety, this model contains 54 defined properties variables and 133 defined state variables listed and described in Appendix C. Table 16 lists the principle property and state variables utilized to determine aircraft, sensor and ordnance performance and behavior within the model.

Table 16. Model Property and State Variables

Aircraft Property and State Variables				
Label	Definition	Type	Dimension	Units
Sortie Duration	Maximum fuel limited flight time	Scalar	Time	HH:MM:SS
Max Velocity	Aircraft maximum velocity	Scalar	Real	knots
Search Velocity	Aircraft velocity while conducting searches	Scalar	Real	knots
Spotting Duration	Aircraft time to complete flight deck spotting	Scalar	Time	HH:MM:SS
Takeoff Duration	Aircraft time to complete takeoff	Scalar	Time	HH:MM:SS
Search Altitude	Aircraft altitude while conducting search operations	Scalar	Real	m
Search Slant Range	Aircraft slant range to surface contact while conducting search operations	Scalar	Real	m

Aircraft Property and State Variables				
CID Duration	Time for aircraft to perform classification of surface contact	Scalar	Time	HH:MM:SS
CID Altitude	Aircraft altitude while classifying a surface contact	Scalar	Real	m
CID Slant Range	Aircraft slant range to surface contact during classification	Scalar	Real	m
Assessment Duration	Time for aircraft to perform battle damage assessment	Scalar	Time	HH:MM:SS
Weapon Altitude	Aircraft altitude during weapon engagements	Scalar	Real	m
Weapon Slant Range	Aircraft slant range during weapon engagements	Scalar	Real	m
Recovery Duration	Aircraft time to complete recovery and landing	Scalar	Time	HH:MM:SS
Scheduled Maintenance Interval	Aircraft flight hours between required maintenance actions	Scalar	Time	HH:MM:SS
Post Flight Maintenance Duration	Time to perform post flight maintenance	Scalar	Time	HH:MM:SS
Unscheduled Maintenance Duration	Time to perform unscheduled maintenance	Scalar	Time	HH:MM:SS
Scheduled Maintenance Duration	Time to perform scheduled maintenance	Scalar	Time	HH:MM:SS
Failure Rate	Aircraft mechanical MTBF	Scalar	Time	HH:MM:SS
Mishap Rate	Aircraft number of flight hours between mishaps	Scalar	Time	HH:MM:SS

Sensor and Ordnance Properties and State Variables				
Label	Definition	Type	Dimension	Units
Search Sweepwidth	EO sensor sweepwidth while conducting search operations	Scalar	Time	HH:MM:SS
Weapon Max Range	Ordnance type dependent maximum range	Scalar	Real	M
Weapon Max Slant Range	Ordnance type dependent maximum slant range	Scalar	Real	M
Weapon Velocity	Ordnance type dependent velocity	Scalar	Real	m/s
Weapon CEP	Ordnance type dependent circular error probable	Scalar	Real	M

b. Object Classifications

This study utilizes two object classifications: events and agents.

(1) Events

Placed in a specific sequence in the model, events represent activities or actions that occur during the simulation. In this study, events represent the sequence of actions that occur during the execution of the expanded kill chain, such as flight deck spotting, takeoff, surveillance and recovery.

(2) Agents

Agents are objects that move freely in the designed system model. Agents in this model represent individual objects or entities that act independently and interact with the entire system and other objects, examples of agents used in this study are the model entities for the RQ-21 Blackjack, MH-60S, and the MQ-8C Fire Scout.

c. Links

Links connect modeled objects. Links are the designed pathways that agents can travel. User defined conditional parameters assign link routing and direct agents to either travel along their current path or select an alternate path with conditions that meet the behaviors of the agent. An example in this model is the direction of aircraft following surface contact classification. Upon classification of a surface contact as hostile, the BLUE aircraft is routed along the link to the weaponeering event, while upon neutral classification the aircraft is routed back to surveillance.

d. Processes

In SIMIO, processes incorporate intelligence in objects (Thiesing and Pegden 2). Intelligence directs an object's behavior in response to events in the system. Processes incorporate dynamic changes to objects in the model. Each process represents a step triggered by an event in the model. The use of single or multiple processes develops model logic. Processes include determination of link selection, changes to object states, agent movement delays in the system or temporarily termination of a sequence of events. Embedded processes in events control the movement of the modeled aircraft, such as the adjustment of an aircraft's fuel state as a function of its sortie duration, or the designation of an aircraft's flight altitude while conducting surveillance.

C. OBJECTIVE

The objective is to model the entire sequence of events representing a FAC/FIAC ASUW expanded end to end kill chain for manned aircraft and UAVs in order to evaluate air vehicles CONOPS for kill chain execution effectiveness. The model incorporates all expanded kill chain events from flight deck spotting, takeoff, surveillance, classification and identification, weapon engagement, post engagement assessment, landing and post flight maintenance. Throughout the model, entities representing the studied manned aircraft and UAVs are exposed to potential loss due to mishap and RED threats as well as in-flight mechanical failures. The objective measures of effectiveness are average detection time (hostile or neutral), number of RED forces killed in a finite time period, and time until 50 percent attrition of RED forces. The objective measure of performance is average cost per kill (C_k^{ave}), defined as the aggregate cost divided by the total number of kills.

1. Aggregate Cost Calculation

The aggregate cost (C^{total}) is the summation of cost incurred due to aircraft loss (L), aircraft operational costs (C^{op}) and the costs of expended ordnance (C^{ord}). In the following sections and equations, y represents the type of aircraft (MH-60S, MQ-8C, or RQ-21) and x identifies individual aircraft. Therefore, the subscript x,y represents the x^{th} aircraft of type y.

a. Cost Due to Aircraft Loss

Costs due to aircraft loss (L) result from effective RED engagements against BLUE aircraft (Loss^{RED}) or BLUE aircraft catastrophic mishaps ($\text{Loss}^{\text{MISHAP}}$). These costs are aircraft type (MH-60, RQ-21, or MQ-8C) dependent.

Sets:

$$\text{x} \in \text{X} = \{0,1,2,...,n\} \quad \text{number of individual aircraft type}$$

$$\text{y} \in \text{Y} = \{1,2,3\} \quad \text{type/model/series of aircraft}$$

$$L = \sum_{x,y} APUC_y * \left(\text{Loss}_{x,y}^{\text{RED}} + \text{Loss}_{x,y}^{\text{MISHAP}}\right)$$

b. Aircraft Operational Costs

Examples of costs due to aircraft operation include fuel, maintenance and personnel. The study calculates operational costs by the summation of the individual aircraft flight hours executed in the simulation (T) multiplied by the average hourly Operation and Support (O&S) cost (C^{hr}). The study calculates average hourly O&S costs (C^{hr}) by dividing the average annual O&S costs by the projected annual flight hours per aircraft. Average hourly O&S costs are aircraft type dependent. Appendix B provides tabulated data and calculations for average hourly O&S costs.

Sets:

$x \in X = \{0,1,2,\ldots,n\}$ number of individual aircraft type

$y \in Y = \{1,2,3\}$ type/model/series of aircraft

$$C^{op} = \sum_{x,y} C_y^{hr} * \mathrm{T}_{x,y}$$

c. Ordnance Costs

Ordnance costs (C^{ord}) include the expense incurred due to the expenditure of ordnance in the execution of a kill chain. The study calculates ordnance costs by the summation of the aircraft ordnance fired (O^{shot}) multiplied by the cost per round (C^{round}). The study models two types of ordnance: AGM-114 HELLFIRE and APKWS-II missiles. Aircraft loadout is restricted to one type of ordnance per simulation.

Sets:

$x \in X = \{0,1,2,\ldots,n\}$ number of individual aircraft type

$y \in Y = \{1,2,3\}$ type/model/series of aircraft

$z \in Z = \{1,2\}$ type ordnance

$$C^{ord} = \sum_{x,\mathrm{y},\mathrm{z}} O_{x,\mathrm{y},\mathrm{z}}^{shot} * \mathrm{C}_z^{round}$$

d. Aggregate Cost Equation

Based on the equations derived in Chapter III.C.1.a-c the complete equation for aggregate cost is:

Sets:

x $\in$ X = $\{0,1,2,\ldots,n\}$ number of individual aircraft type

y $\in$ Y = $\{1,2,3\}$ type/model/series of aircraft

z $\in$ Z = $\{1,2\}$ types of ordnance

$$\mathrm{C}^{total} = L + \mathrm{C}^{op} + \mathrm{C}^{ord}$$

$C^{total} =$ aggregate cost

L = cost incurred due to aircraft loss (III.C.1a)

C^{op} = aircraft operational cost (III.C.1b)

C^{ord} = ordnance cost (III.C.1c)

2. Red Kill Determination

Total RED kills (K^{RED}) is determined through the summation of all BLUE aircraft RED kills during a simulation of finite length. $K_{x,y}$ represents the number of RED killed by aircraft x of type y.

Sets:

x $\in$ X = $\{0,1,2,\ldots,n\}$ number of individual aircraft type

y $\in$ Y = $\{1,2,3\}$ type/model/series of aircraft

$$K^{RED} = \sum_{x,y} K_{x,y}$$

3. Aggregate Cost Equation

Based on equations developed in III.C.1d and IIII.C.2, the resultant equation for the study's MOP of average cost per kill (C_k^{ave}) is:

$$C_k^{ave} = \frac{C^{total}}{K^{RED}} \quad \text{where,}$$

$$\mathrm{C}^{total} = L + \mathrm{C}^{op} + \mathrm{C}^{ord} \quad \text{(III.C.1d)}$$

$$K^{RED} = \sum_{x,y} K_{x,y} \quad \text{(III.C.2)}$$

D. SCOPE, ASSUMPTIONS AND LIMITATIONS

The model is structured to represent 24 hours per day operations under the following baseline conditions:

- Operational Area – 3927 nm^2
- RED force level – 20
- Neutral shipping level – 100
- Simulation duration – 30 days

The size of the operational area approximates a semi-circular area with a 50 nm radius and the BLUE air capable ship located at the center. These dimensions enable the deployed air vehicles to remain within their communication and navigation system maximum range constraints.

Despite a continuous 24-hour run time, the model is strictly designed to evaluate day only electro-optical sensor performance. This limits aircraft flight operations to 12 hours of daylight operations per day. Aircraft maintenance activities occur 24 hours a day. The model does not take into account the effects of weather, with the exception of RED visual detection range and RED probability of detecting BLUE via the U.S. Army Night Vision Integrated Performance Model software (U.S. Army, NV-IPM V1.2).

E. OVERALL MODEL LOGIC

While kill chains generally contain the sequence of tasks FIND, FIX, TRACK, TARGET, ENGAGE and ASSESS, this model redefines these tasks with the following events: SURVEILLANCE, CLASSIFICATION, WEAPON ENGAGEMENT and ASSESSMENT. The inclusion of FLIGHT DECK SPOTTING, TAKEOFF, and AIRCRAFT MAINTENACE further develops the kill chain. Figure 5 describes an overview of the basic logic for BLUE aircraft in the model.

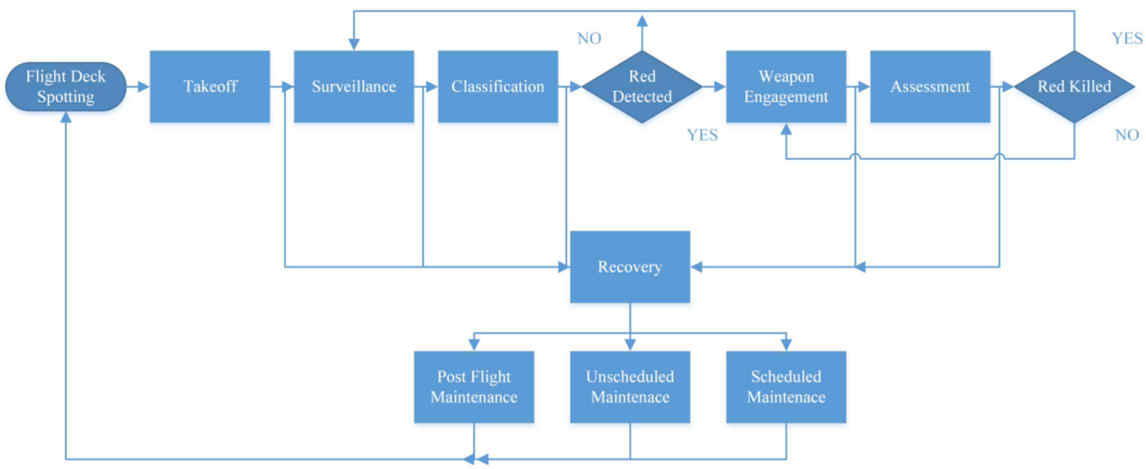

Figure 5. Expanded Kill Chain BLUE Logic

1. Blue Aircraft Routing Overview

Inherent properties of the modeled aircraft (e.g., maximum velocity and scheduled maintenance interval) or properties assigned to the aircraft during the execution of the simulation, route aircraft through the simulated extended kill chain. Upon initialization of the simulation, the user-defined number of aircraft enters the modeled kill chain at the FLIGHT DECK SPOTTING event. This event represents maintenance, on-board fuel and ordnance mission ready aircraft. After flight deck spotting, aircraft transition to the TAKEOFF event. The takeoff event represents the transition from on-deck to in-flight configuration. From TAKEOFF, aircraft commence search efforts via the SURVEILLANCE event. Upon aircraft detection of a surface contact, the aircraft transitions to the CLASSIFICATION event where the contact identification as hostile

(RED) or neutral occurs. At this decision point, aircraft follow one of two routes; upon identification of a neutral contact, the aircraft is rerouted to SURVEILLANCE to reinitiate the search for additional surface contacts, following identification of a hostile (RED) contact, aircraft are directed to the WEAPON ENGAGEMENT event for hostile prosecution. At the conclusion of WEAPON ENGAGEMENT, aircraft perform battle damage assessment and obtain confirmation of a RED kill or the requirement for a weapon re-engagement. RED kill confirmation reroutes the aircraft to SURVEILLANCE for additional targets. The requirement for weapon re-engagement reroutes aircraft to WEAPON ENGAGEMENT. The simulation monitors BLUE aircraft fuel state, mechanical failures and ordnance payload throughout the simulation. Depletion of ordnance, reaching minimum operational fuel, or suffering an in-flight mechanical failure routes BLUE aircraft for landing via the RECOVERY event. Completion of RECOVERY routes aircraft to POST FLIGHT MAINTENANCE, UNSCHEDULED MAINTENANCE or SCHEDULED MAINTENANCE based on the landing requirement conditions. Maintenance event completion routes aircraft to FLIGHT DECK SPOTTING and completes a kill chain sequence. Section G provided additional kill chain event and internal event process details.

F. RED THREAT INTERACTION

Within the model, the capability for RED surface contacts to employ surface to air missiles (SAM) against BLUE aircraft is incorporated in the process logic during the SURVEILLANCE, CLASSIFICATION, WEAPON ENGAGEMENT and ASSESSMENT events. Figure 6 describes an overview of the basic logic for RED threat interaction with BLUE aircraft contained in the model.

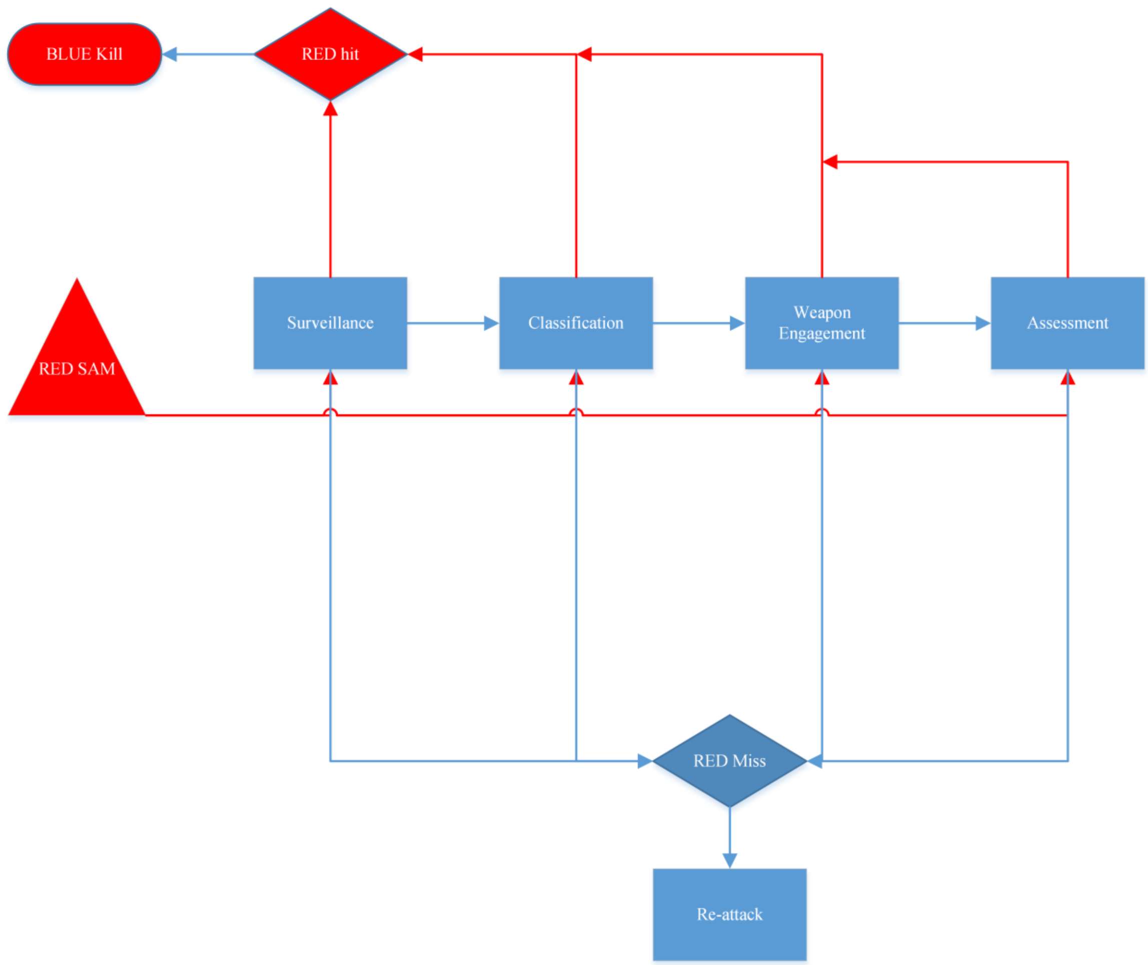

Figure 6. RED Threat Interaction

1. Red Threat Logic Overview

Process logic in the SURVEILLANCE, CLASSIFICATION, WEAPON ENGAGEMENT and ASSESSMENT events compares the BLUE aircraft's altitude and slant range from the RED surface contact to the maximum altitude and range of the RED SAM. If the BLUE aircraft is within the RED threat envelope, the comparison of BLUE and RED detection and engagement rates determines subsequent actions. If the duration of the RED detect to engage sequence is less than BLUE, RED engages BLUE with a SAM. If the BLUE detect to engage sequence is less than RED, BLUE proceeds to the next event in the kill chain process. RED weapon engagement results in a BLUE kill with a RED hit or BLUE routed to the REATTACK event with a RED miss. The REATTACK event represents a compressed kill chain with abbreviated classification and weapon engagement durations. The comparison of detect to engage rate is repeated in the REATTACK event with the following outcomes; RED executes an additional weapon engagement or BLUE is routed to WEAPON ENGAGEMENT. Section G.2.h presents additional RED threat interaction and internal event process details.

G. SIMULATION DESIGN

Processes internal to events (examples include TAKEOFF, SURVEILLANCE, ASSESSMENT and RECOVERY) modify modeled aircraft properties and actions. These modifications direct kill chain route selection. An example in the study is aircraft being routed for recovery upon minimum fuel or the aircraft's destruction in the event of a BLUE aircraft catastrophic mishap. The following sections describe in detail the processes in each event and the aircraft actions that result at the conclusion of the event execution.

1. Recurring Processes

Four internal processes continuously evaluate modeled aircraft material conditions: fuel state monitoring, aircraft in-flight mechanical failure monitoring, aircraft scheduled maintenance interval monitoring and aircraft catastrophic mishap monitoring.

a. Fuel State Monitoring

The model determines aircraft current fuel state through the comparison of executed flight time versus aircraft type-dependent maximum sortie length. When aircraft flight time equals its maximum sortie duration, the aircraft is routed for recovery.

b. Aircraft In-flight Mechanical Failure Monitoring

Initial flight deck spotting assigns modeled aircraft a flight time until the occurrence of in-flight mechanical failure. The in-flight failure time is randomly generated based on an exponential distribution with a mean of the aircraft type-dependent MTBF. As the aircraft conducts flight operations, its executed flight time is continuously compared to the randomly assigned in-flight failure time. When flight time exceeds the in-flight failure time, the aircraft suffers a mechanical in-flight failure and is routed for recovery and unscheduled maintenance. Aircraft completion of unscheduled maintenance generates a new randomly assigned in-flight failure time with the previously described random distribution. With the exception of the initial flight deck spotting, all random failure time reassignments occur at the completion of unscheduled maintenance.

c. *Schedule Maintenance Interval Monitoring*

During the simulation, aircraft cumulative executed flight time is compared to its type-dependent user defined scheduled maintenance interval property. When an aircraft's cumulative flight time equals its scheduled maintenance interval, the aircraft is routed for recovery and scheduled maintenance. Upon completion of scheduled maintenance, the cumulative flight time counter resets to zero and the aircraft resumes flight operations until the cumulative flight clock again equals the defined scheduled maintenance interval.

d. *Catastrophic Mishap Monitoring*

Simulation initiation assigns modeled aircraft a flight time until the occurrence of a catastrophic mishap. The catastrophic mishap time is randomly generated based on an exponential distribution with a mean of the aircraft type-dependent mishap rate. As the aircraft conducts flight operations, its cumulative executed flight time is continuously compared to the randomly assigned mishap time. When flight time exceeds the mishap time, the aircraft suffers a catastrophic mishap, is destroyed and removed from the simulation. Figure 7 depicts the process for continuous aircraft monitoring between the surveillance and classification events. Arrows in blue indicate the standard routing that occurs when monitored values do not exceed thresholds.

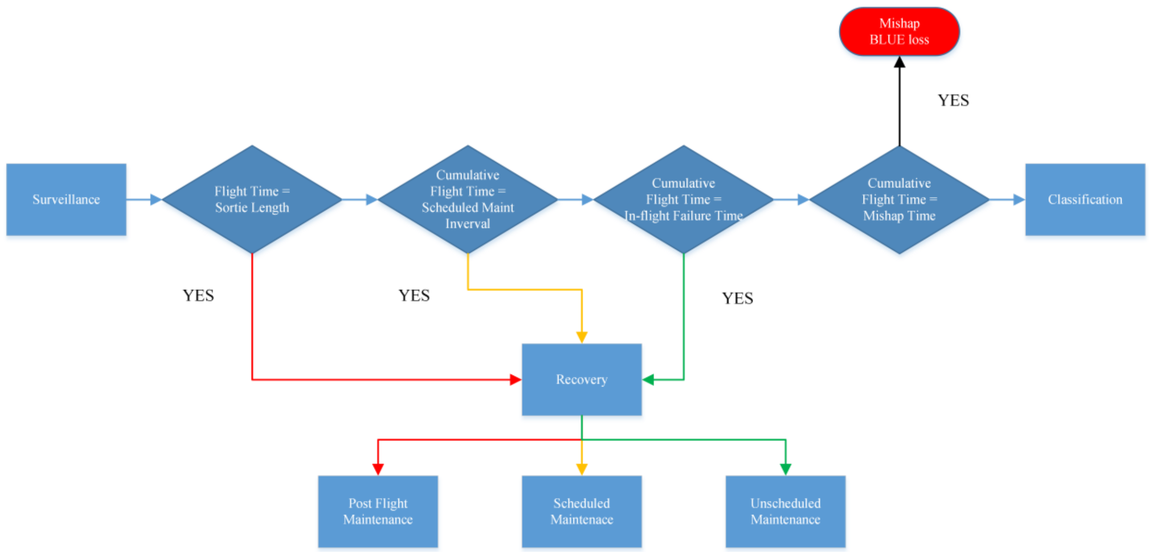

Figure 7. Model Continuous Aircraft Monitoring Process

2. Kill Chain Event-Specific Processes

Each sequence of the expanded kill chain selectively directs and modifies modeled aircraft via processes internal to the kill chain events. The following sections detail the processes in each kill chain event and its impact on the aircraft's behavior or material condition.

a. Model Initiation

Model initiation creates aircraft available for kill chain execution based on user-defined quantities. In the study, the number of RQ-21, MQ-8C and MH-60S aircraft varies based on the CONOPS selected for evaluation. BLUE aircraft creation assigns values for initial ordnance payloads, sortie duration, ordnance circular error probable (CEP), and ordnance probability of kill based on the user selected ordnance type (HELLFIRE or APKWS-II) and RED target dimensions. Additionally, the calculation of RED probability of kill based on RED ordnance CEP and BLUE aircraft type-dependent target dimensions is performed. Appendix D provides probability of kill calculation details.

b. Flight Deck Spotting

Once created via simulation initiation, aircraft transition to an operationally ready state through the flight deck spotting event. Flight deck spotting represents the time and sequence of events required to move an aircraft from a storage location (air capable ship hangar) to the flight deck and the accomplishment of the aircraft's material readiness via ordnance loading, fueling, and pre-flight maintenance actions. Processes internal to the flight deck spotting event are:

- Ordnance payload set to maximum aircraft type-dependent loadout
- Fuel loadout set to achieve established sortie duration

The model incorporates aircraft type-dependent flight deck spotting duration variability through a randomly generated time with a triangular distribution having the following parameters:

- Mean time: aircraft spotting duration
- Minimum time: 0.75 * mean(spotting duration)
- Maximum time: 1.5 * mean(spotting duration)

c. Takeoff

Model links route aircraft to TAKEOFF upon completion of flight deck spotting. The takeoff event initiates aircraft flight time calculations and fuel state, scheduled maintenance, mishap and in-flight failure monitoring. Takeoff event duration is aircraft type-dependent and the model introduces variability via a randomly generated time with a triangular distribution having the following parameters:

- Mean time: aircraft takeoff duration
- Minimum time: 0.75 * mean(takeoff duration)
- Maximum time: 1.5 * mean(takeoff duration)

d. Surveillance

Within the SURVEILLANCE event, BLUE aircraft conduct searches via electro-optical sensors and RED ships conduct unaided (naked eye) searches for BLUE aircraft.

Routing to surveillance assigns BLUE aircraft optimum search altitudes and sensor to target slant ranges based on BLUE sensor capabilities, imagery requirements and RED target dimensions for contact acquisition. Sections d.1 and d.2 detail the internal process calculations for BLUE and RED detection times.

(1) Blue Detection Time

The model calculates individual BLUE aircraft detection rates based on the sweepwidth of the BLUE sensor, the velocity of the BLUE aircraft and the size of the search area. The model adjusts the individual aircraft search rate for the number of RED and neutral ships present in the search area to determine a non-contact specific (RED or neutral contact) detection time. Continuous detection time is sampled from an exponential distribution with a mean of the individual aircraft calculated search time.

The summation of individual aircraft search efforts determines a composite detection time and incorporates the ability for multiple BLUE aircraft to search simultaneously. Prior to the initiation of each surveillance event, composite detection recalculates based on the current number of BLUE aircraft simultaneously searching. Additionally, during the execution of a simulation, BLUE detection time adjusts for changes in the number of RED within the search area following the BLUE destruction of RED contacts.

(2) Red Time to Detect BLUE

Similar to BLUE detection time, RED time to detect BLUE is based on the quantity and visual sweepwidth of the RED vessels and the velocity and quantity of the BLUE aircraft conducting surveillance. RED visual sweepwidth is dependent on the dimensions, altitude and slant range of the BLUE aircraft conducting surveillance events. The summation of individual RED search efforts determines a composite mean RED detection time. Implementation of a continuous search model is performed through the use of an exponential distribution with a mean of the RED composite detection time. Appendix E provides equations for RED detection time and sweepwidth.

As depicted in Figure 8, the model compares the BLUE and RED detection times. If BLUE detection time is less than RED detection time, links route the BLUE aircraft to CLASSIFICATION (Section 2.e). If BLUE detection time is greater than RED detection time, the RED threat executes a weapons engagement against the BLUE aircraft. BLUE and RED detection times respond to the number of RED threats and the number of BLUE aircraft searching. BLUE detection time decreases with the inflow of additional BLUE aircraft into the SURVEILLANCE event and increases with RED threat destruction and as BLUE aircraft exit SURVEILLANCE via linkage to CLASSIFICATION.

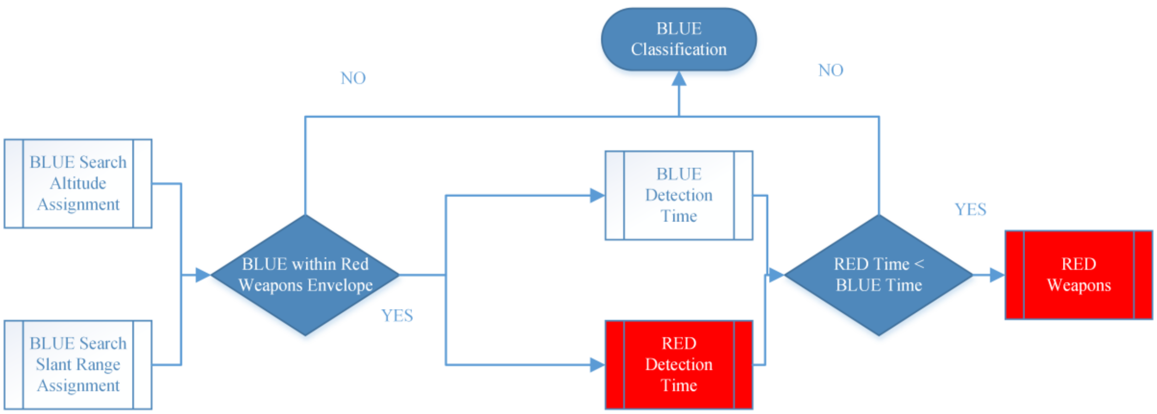

Figure 8. Model Surveillance Event

e. Classification

Upon the BLUE detection of a surface contact that is uncontested by a RED weapon engagement, a BLUE aircraft is routed to the CLASSIFICATION event. Classification performs the positive identification of the surface contact in order to discriminate RED from neutral contacts. Classification event processes adjust BLUE aircraft altitude and sensor to target slant range for contact classification and identification based on BLUE sensor capabilities, imagery requirements and RED target dimensions. Classification results in the determination that the contact is RED or neutral. Classification event duration is aircraft type-dependent and variability is introduced via a randomly generated time with a triangular distribution having the following parameters:

- Mean time: aircraft classification duration
- Minimum time: 0.75 * mean(classification duration)

- Maximum time: 1.5 * mean(classification duration)

During the CLASSIFICATION event, BLUE aircraft are at risk to RED detection and weapon engagement. The model determines RED time to detect BLUE via a discrete calculation based on RED glimpse probability, field of view and scan rate. Appendix F presents equations for RED time to detect BLUE during the CLASSIFICATION event. BLUE classification time is compared to RED detection time. If BLUE classification time is less than RED time to detect BLUE, the BLUE aircraft is routed to WEAPON ENGAGEMENT. If BLUE classification time is greater than RED detection time the RED threat executes a weapon engagement against the BLUE aircraft. Figure 9 depicts the sequence of events and processes in the CLASSIFICATION event.

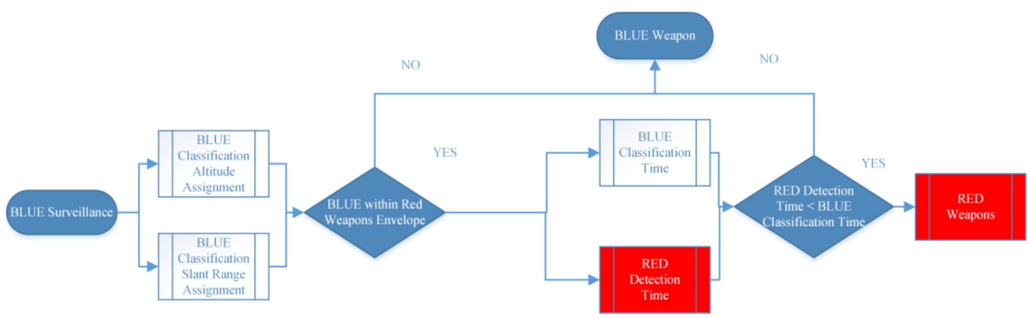

Figure 9. Model Classification Event

Prior to route advancement, BLUE aircraft perform fuel state, in-flight mechanical failure, scheduled maintenance interval and mishap monitoring to filter out aircraft that require recovery and maintenance from further kill chain events. Aircraft that remain are re-routed to SURVEILLANCE upon the classification of the surface contact as neutral and routed to WEAPON ENGAGEMENT for surface contacts classified as RED.

f. Weapon Engagement

After classification of a surface contact as RED, model links route uncontested BLUE aircraft to WEAPON ENGAGEMENT for target prosecution. BLUE aircraft remain at previously assigned classification altitude and sensor to target slant range in the execution of weapon engagements. Weapon time of flight (TOF) and release times determine weapon engagement durations. Weapon TOF calculations are ordnance velocity and slant range dependent and vary based on the type of ordnance employed. Weapon release times are aircraft type-dependent. The model introduces weapon engagement event duration variability via a randomly generated time with a triangular distribution having the following parameters:

- Mean time: Weapon TOF + aircraft weapon release time
- Minimum time: 0.75 * mean(Weapon TOF + aircraft weapon release time)
- Maximum time: 1.5 * mean(Weapon TOF + aircraft weapon release time)

Similar to CLASSIFICATION, BLUE aircraft are at risk to RED detection and weapon engagement during WEAPON ENGAGMENT. Figure 10 depicts the model comparison of BLUE weapon engagement times to RED detection and weapon engagement times in order to determine the "first shooter."

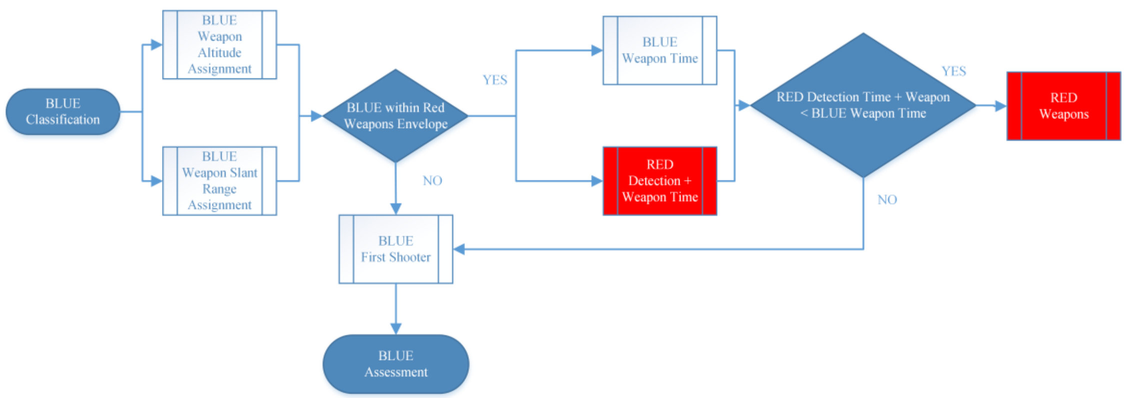

Figure 10. Model Weapon Engagement Event

Prior to route advancement, aircraft fuel state, in-flight mechanical failure, scheduled maintenance interval and mishap monitoring is performed to filter out aircraft that require recovery and maintenance from further kill chain events. Aircraft that remain are routed to ASSESSMENT.

g. Assessment

The ASSESSMENT event performs battle damage assessments to determine the effectiveness of BLUE weapon engagements. BLUE assessment altitude and slant range is assigned, followed by the calculation of BLUE probability of kill. The model compares BLUE probability of kill to a randomly generated number with a uniform distribution between 0 and 1. If BLUE probability of kill is greater than the random number the result is a RED kill and model links route the BLUE aircraft to SURVEILLANCE following fuel, ordnance, scheduled maintenance, in-flight failure and mishap monitoring, repeating the kill chain sequence. If the BLUE probability of kill is less than the random number the model reroutes the BLUE aircraft to WEAPON ENGAGEMENT for additional weapons employment. BLUE ordnance type-dependent CEP and the RED target dimensions determine BLUE probability of kill (Adams pars. 2-3). Appendix D presents probability of kill calculations.

BLUE assessment duration is aircraft type-dependent and the model introduces real world variability with a triangular distribution having the parameters:

- Mean time: aircraft assessment time
- Minimum time: 0.75 * mean(aircraft assessment time)
- Maximum time: 1.5 * mean(aircraft assessment time)

Similar to the RED threat interaction during WEAPON ENGAGEMENT, BLUE aircraft are at risk to RED weapon engagements during ASSESSMENT. If the BLUE aircraft is unsuccessful in killing the RED threat, the model compares BLUE assessment time to the RED detection and weapon time. If the BLUE assessment time is less than the RED time, the BLUE aircraft is rerouted to WEAPON ENGAGEMENT. If the BLUE time is greater than the RED time, the RED threat executes a weapon engagement against the BLUE aircraft. Figure 11 depicts the processes in the ASSESSMENT event.

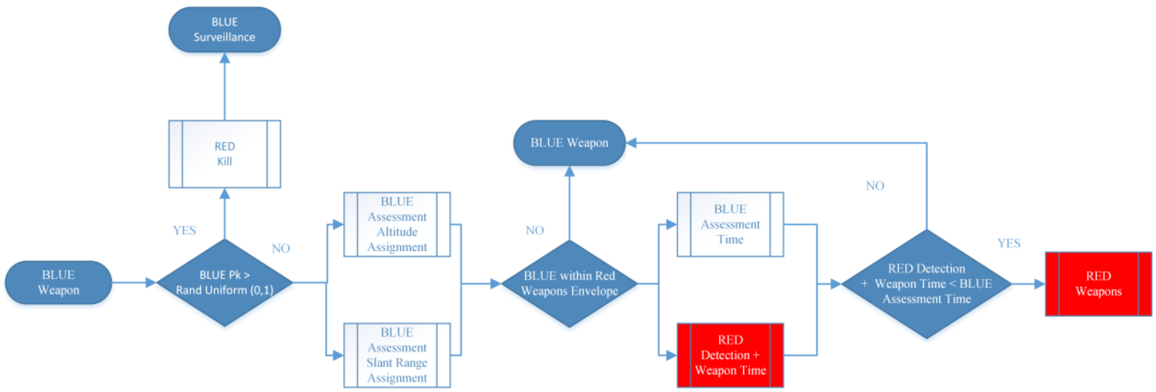

Figure 11. Model Assessment Event

h. RED Weapon Engagements

Similar to BLUE weapons engagements, a comparison of RED probability of kill to a randomly assigned number with a uniform distribution between 0 and 1 determines the success of RED weapons engagements versus BLUE aircraft. Successful RED weapons engagements occur when RED probability of kill is greater than the random number, resulting in a BLUE KILL. Unsuccessful RED weapons engagement occurs when RED probability of kill is less than the random number and route the BLUE aircraft to RE-ATTACK. RED ordnance CEP and the BLUE aircraft type-dependent target dimensions determine RED probability of kill. Appendix D presents the equations for probability of kill calculations. Figure 12 depicts the processes for RED weapon engagement.

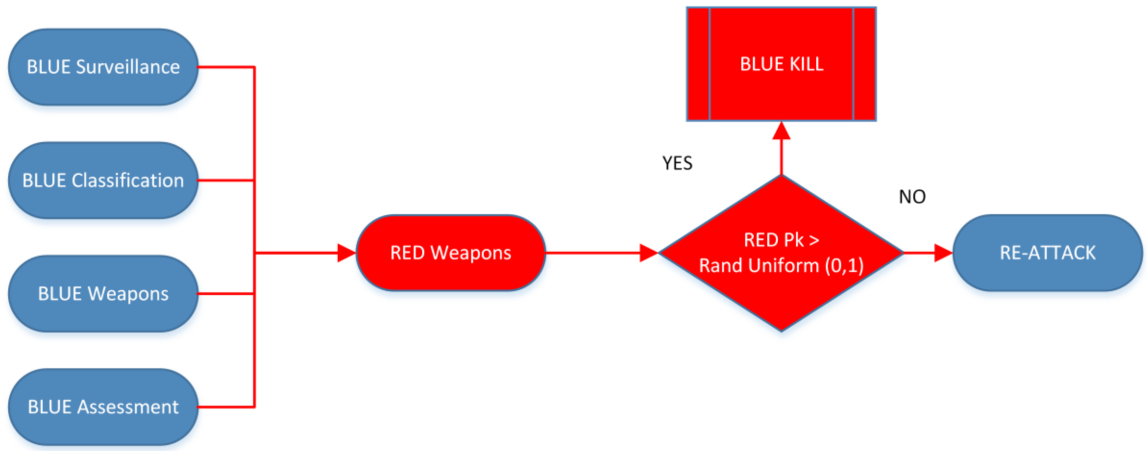

Figure 12. Model RED Weapon Engagement

i. Re-attack

The model incorporates the RE-ATTACK event to account for actions that occur after an unsuccessful RED weapons engagement of BLUE. Based on the time of the RED attack against BLUE, the model determines the required actions in the RE-ATTACK event. Section i.1 and i.2 and Figure 13 describe and depict the processes in the RE-ATTACK event.

(1) Unsuccessful RED weapons engagement against BLUE during SURVEILLANCE

The comparison of two times determines the actions after an unsuccessful RED weapons engagement during BLUE SURVEILLANCE.

- BLUE – based on RED's engagement and miss of BLUE, BLUE's time to classify RED is reduced. The model randomly assigns a BLUE quick classification time with a triangular distribution having the parameters (mean: 0.4*aircraft classification time, min: 0.2*mean(aircraft classification time), max: 0.6*mean(aircraft classification time)).
- RED – based on RED's knowledge of BLUE's position, RED's time to re-engage BLUE is reduced. RED's re-engagement time is the summation of RED re-acquire time plus RED weapon time. The model randomly assigns RED re-acquire time based on RED detection time during BLUE classification and applies a triangular distribution with the parameters (mean: 0.3*RED detection time during BLUE classification, min: 0.2*mean(RED detection time during BLUE classification), max: 0.4*mean(RED detection time during BLUE classification)). The model

sums RED re-acquire time with RED weapon time to determine RED re-engagement time.

If BLUE quick classification time is less than RED re-engagement time, the model routes the BLUE aircraft to BLUE WEAPON. If BLUE quick classification time exceeds RED re-engagement time the RED threat executes an additional weapon engagement against the BLUE aircraft.

(2) Unsuccessful RED weapons engagement during BLUE CLASSIFICATION, WEAPON ENGAGEMENT or ASSESSMENT

The comparison of two times determines the actions after an unsuccessful RED weapons engagement during BLUE CLASSIFICATION, WEAPON ENGAGEMENT or ASSESSMENT.

- BLUE–based on BLUE's knowledge of RED's position and RED's engagement of BLUE, BLUE's time to re-acquire and engage RED is reduced. The model randomly assigns BLUE quick attack time based on a triangular distribution with the parameters (mean: 0.3*BLUE classification time, min: 0.2*mean(BLUE classification time), max: 0.4*mean(BLUE classification time)).
- RED–the summation of RED re-acquire time plus RED weapon time (Section i.1)

Similar to the time comparison results in Section i.1, if BLUE time is less than RED time, the model routes BLUE aircraft to WEAPON ENGAGEMENT. If BLUE time exceeds RED time, the RED threat executes an additional weapon engagement against the BLUE aircraft.

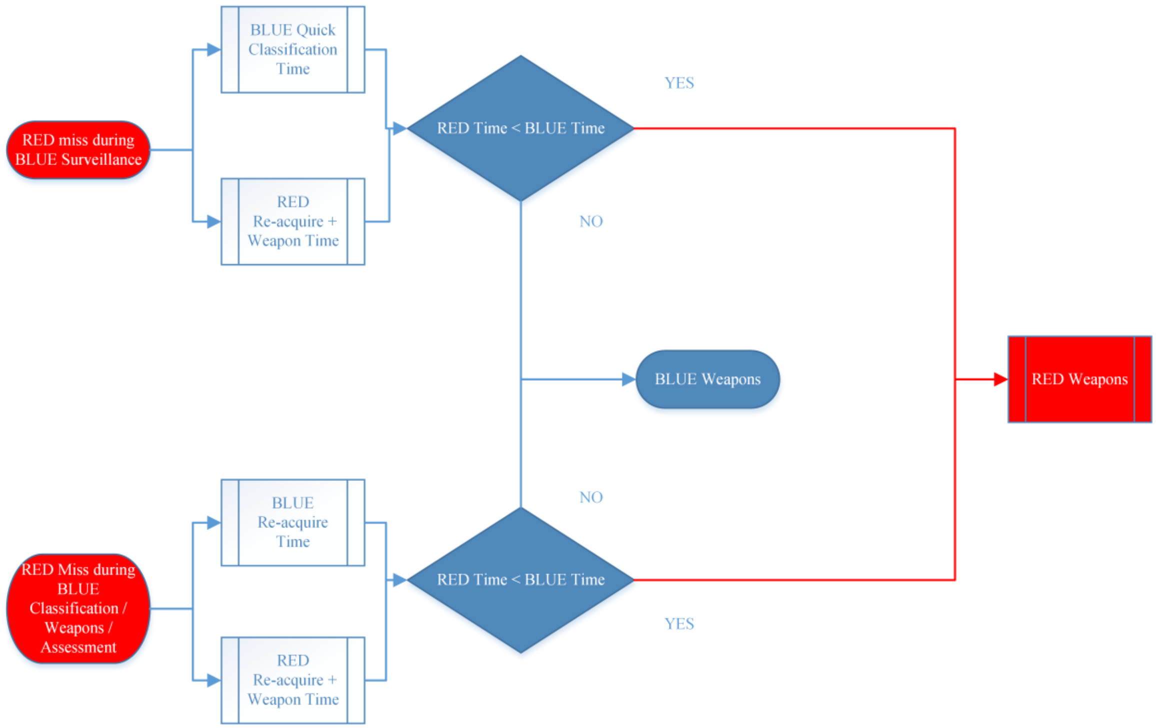

Figure 13. Model Re-Attack Event

j. Recovery

Upon weapon payload depletion, minimum fuel state, in-flight mechanical failure flight time equaling scheduled maintenance interval or the termination of day-time flight operations, the model routes BLUE aircraft to RECOVERY. BLUE recovery duration is aircraft type-dependent and the model introduces real world variability with a triangular distribution having the parameters:

- Mean time: aircraft recovery time
- Minimum time: 0.75 * mean(aircraft recovery time)
- Maximum time: 1.5 * mean(aircraft recovery time)

k. Maintenance Activities

Following recovery, the model routes BLUE aircraft to the appropriate maintenance activity based on recovery conditions. Ordnance depletion of minimum fuel state routes BLUE aircraft to POST FLIGHT MAINTENANCE. In-flight mechanical failure routes BLUE aircraft to UNSCHEDULED MAINTENANCE. When BLUE aircraft flight time exceeds a scheduled maintenance interval, the model routes BLUE aircraft to SCHEDULED MAINTENANCE. The duration of the maintenance activities is aircraft type-dependent and the model incorporates variability through a triangular distribution with a mean of the associate mean maintenance activity time, a minimum of 0.75 the associated mean maintenance activity time, and a maximum of 1.5 the associated mean maintenance activity time. All maintenance activities refuel and rearm BLUE aircraft.

After recovered at the conclusion of daylight flight operation, the model compares the BLUE aircraft cumulative flight time to the aircraft type-dependent scheduled maintenance interval. If the cumulative flight time is within 5 hours of the maintenance interval, the model routes the aircraft to SCHEDULED MAINTENANCE in order to increase the aircraft's available flight time for flight operations the subsequent day. Additionally, upon recovery the model evaluates aircraft to determine if multiple conditions initiated recovery. If multiple conditions exist, the model prioritizes BLUE aircraft maintenance in the following order; SCHEDULED MAINTENANCE, UNSCHEDULED MAINTENANCE, and POST FLIGHT MAINTENANCE. For example, BLUE aircraft recovery due to an in-flight mechanical failure and a scheduled maintenance interval, results in the aircraft routing to SCHEDULED MAINTENACE where the model executes scheduled maintenance and the repair of the in-flight mechanical failure.

l. Unmanned Vehicle Control Limitations

The designed capacity of the unmanned aircraft ground control station (GCS) limits the quantity of unmanned aircraft conducting flight operations. The model incorporates this constraint through monitoring the number of BLUE unmanned aircraft airborne. Within the TAKEOFF event, each unmanned aircraft takeoff increments a counter. Conversely, within the MAINTENANCE events, upon a BLUE unmanned aircraft catastrophic mishap or a successful RED weapon engagement against a BLUE unmanned aircraft the model decrements the counter. The counter total is compared to the GCS control limit. The model restricts additional unmanned aircraft takeoffs when the counter equals or exceeds the GCS control limit. The count's reduction below the GCS control limit de-activates the takeoff restriction.

3. Joint Engagement Simulation Modifications

Section G.2 describes the kill chain event sequence for independent aircraft target detection, classification and prosecution. In order to simulate multiple aircraft joint kill chain execution, the model incorporates additional logic and events to enable aircraft to perform as "hunters" or "hunters and killers." "Hunters" are unarmed aircraft and function solely as surface contact detection and classification platforms while "hunter and killers" are equipped with on-board ordnance and perform detection, classification and weapon engagement functions. Sections 3.a details the additional design features to incorporate joint engagements.

a. Pre and Post Surveillance Routing

BLUE aircraft routing pre and post-SURVEILLANCE is based on the following conditions.

(1) Unarmed BLUE aircraft – following detection the model routes unarmed aircraft to CLASSIFICATION. If CLASSIFICATION yields a positive identification of a neutral contact, the model re-routes the unarmed aircraft to SURVEILLANCE. If CLASSIFICATION yields a positive identification of a RED contact, the unarmed aircraft maintains target tracking until join-up and target hand-off to an armed BLUE aircraft.

(2) Armed BLUE aircraft pre-surveillance (Figure 14) - if an unarmed BLUE aircraft has positively identified a RED contact, the armed aircraft bypasses SURVEILLANCE and CLASSSIFICATION and the model routes the armed BLUE aircraft to assume the WEAPON ENGAGEMENT and ASSESSMENT functions for the unarmed aircraft's identified RED target. Following the target hand-off, the unarmed BLUE aircraft resumes surveillance. If an unarmed BLUE aircraft has not identified a RED contact, the model routes the armed aircraft to SURVEILLANCE.

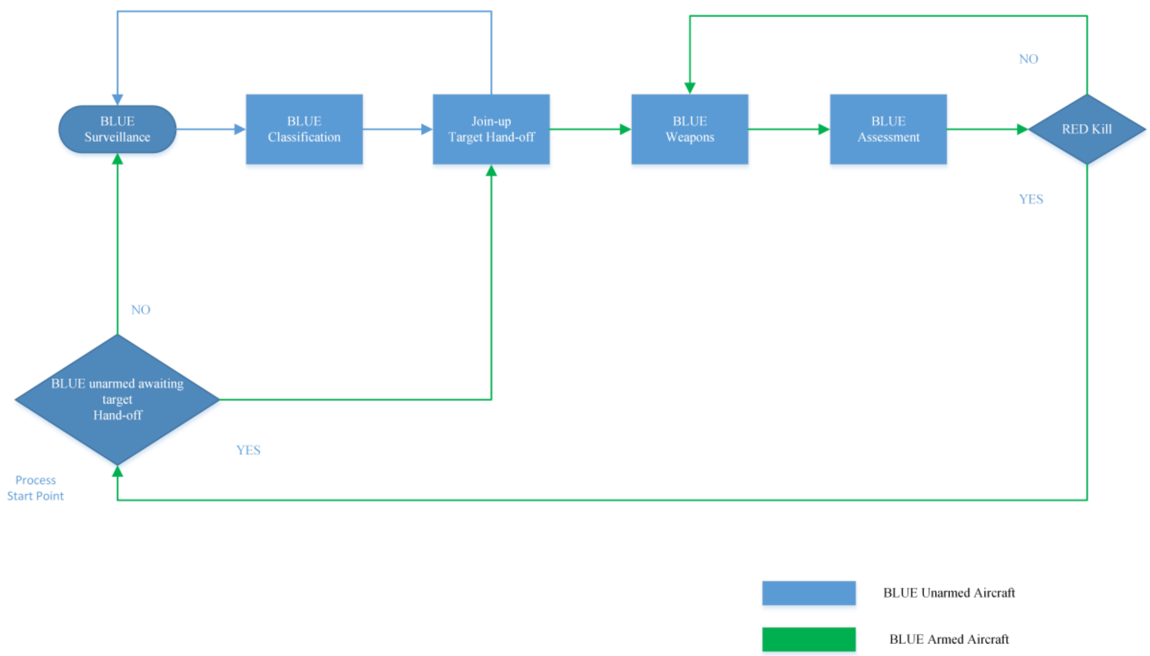

Figure 14. Model Pre-Surveillance Joint Engagement

(3) Armed BLUE aircraft post-surveillance (Figure 15) – similar to section (a.2), armed BLUE aircraft bypass CLASSIFICATION and perform WEAPON ENGAGEMENT and ASSESSMENT functions in the event an unarmed BLUE aircraft positively identifies a RED target. Following the target hand-off, the unarmed aircraft resumes surveillance. If an unarmed BLUE aircraft has not identified a RED contact, the model routes armed aircraft upon completion of SURVEILLANCE to CLASSIFICATION. The model prioritizes the prosecution of RED targets classified by unarmed BLUE aircraft to minimize the exposure of unarmed BLUE aircraft to RED weapons.

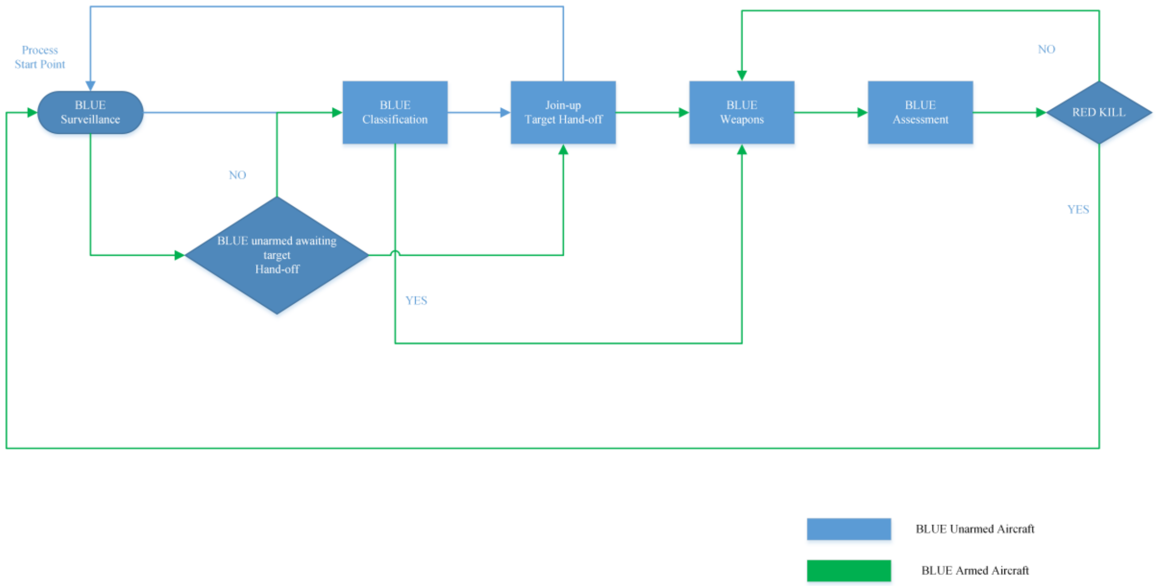

Figure 15. Model Post-Surveillance Joint Engagement

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IV. RESULTS

This chapter introduces the results from the simulation of the designed CONOPS. We present the results in terms of achieved measurements of effectiveness and measurement of performance for each CONOPS evaluated. We then compare and perform causal analysis of the CONOPS relative performance.

A. INTRODUCTION

The study tested four CONOPS and six aircraft compositions to determine an efficient combination of manned and unmanned aircraft in the execution of FAC/FIAC ASUW kill chains tested four CONOPS and six variations. Table 17 lists the evaluated CONOPS and the associated aircraft quantities and tasks. We collected aircraft performance, maintenance, mishap, sensor, ordnance and cost data in support of accurate aircraft modeling. The study estimates unavailable sensor performance parameters due to classification or proprietary rights through the implementation of equations and calculations obtained from the Institute of Defense Analyses (Koretsky, Taylor and Nicoll 13–19), Surveillance and Reconnaissance Systems: Modeling and Performance Prediction (Leachtenauer 32) and Electro-Optical Tracking Systems Considerations (Downey and Stockum 82–83). We determined RED visual search parameters with the aid of the U.S. Army Night Vision Integrated Performance Model software (U.S. Army, NV-IPM V1.2), A Model for Visual Detection of Aircraft by Ground Observers (Poe 6–8), and Visual Search Processes of Coast Guard Aircrewmen (Jones 25). Appendix G provides the baseline model parameters.

Table 17. Evaluated CONOPS

	MH-60 (quantity)	MQ-8 (quantity)	RQ-21 (quantity)	Tasks
CONOPS 1A	3	3	0	MQ-8: RED detection, classification and targeting MH-60: RED detection, classification, targeting and prosecution (via HELLFIRE)
CONOPS 1B	6	0	0	MH-60: RED detection, classification, targeting and prosecution (via HELLFIRE)
CONOPS 2A	3	3	0	MQ-8: RED detection, classification, targeting and prosecution (via APKWS II) MH-60: RED detection, classification, targeting and prosecution (via APKWS II)
CONOPS 2B	6	0	0	MH-60: RED detection, classification, targeting and prosecution (via APKWS II)
CONOPS 3	4	0	6	RQ-21: RED detection, classification and targeting MH-60: RED detection, classification, targeting and prosecution (via APKWS II)
CONOPS 4	0	3	9	RQ-21: RED detection, classification and targeting MQ-8: RED detection, classification, targeting and prosecution (via APKWS II)

B. RESULTS

We utilized SIMIO to simulate 2000 replications per CONOPS for 12000 total replications with a combined run time of 152 minutes. We explored numbers of replications exceeding 2000 with no impact on the estimated results. Each replication simulated 30 days of 12 hours of daylight flight operations per day for the CONOPS determined quantities of aircraft. We then compared the mean measures of effectiveness (MOE) and measure of performance (MOP) achieved by each CONOPS in order to select the most efficient aircraft combination for the execution of FAC/FIAC ASUW kill chains. Table 18 presents the mean and standard error (SE) for the MOP and MOE performance of all evaluated CONOPS ranked by MOP

Table 18. CONOPS MOP and MOE Performance

CONOPS	Aircraft		**MOP**		**MOE #1**		**MOE #2**		**MOE #3**		**Mean BLUE Losses (# of aircraft)**	SE
	Type	#	Mean Cost per RED Kill ($M FY16)	SE	Mean Number of RED Kills	SE	Mean Time till 50% RED Attrition (Hours)	SE	Mean BLUE Detection Time (Hours)	SE		
3	MH-60S RQ-21A	4 6	2.0	0.044	19.95	0.015	4.7	0.103	0.8	0.006	4.0	0.069
4	MQ-8C RQ-21A	3 9	2.4	0.038	19.81	0.030	4.5	0.105	0.9	0.012	4.8	0.087
2B	MH-60S	6	3.2	0.062	19.97	0.008	5.2	0.125	0.5	0.004	1.6	0.043
1B	MH-60S	6	3.3	0.062	19.97	0.008	5.2	0.124	0.5	0.004	1.6	0.042
2A	MH-60S MQ-8C	3 3	4.9	0.063	19.88	0.017	6.1	0.219	0.7	0.005	2.6	0.049
1A	MH-60S MQ-8C	3 3	5.0	0.066	19.85	0.024	17.0	0.437	1.1	0.006	2.5	0.049

1. MOP—Cost per RED Kill

Mean cost per RED kill varied from a minimum of 2.0 $M FY16 for CONOPS 3 to a maximum of 5.0 $M FY16 for CONOPS 1A. From the results presented in Table 19, across all tested aircraft configurations a maximum of 0.8 percent difference exists in the quantity of RED kills, therefore the primary determinate of cost per RED kill is the CONOPS total cost. Total cost is composed of three elements; cost due to aircraft attrition, aircraft operating and ordnance expenditure costs. Cost due to BLUE aircraft attrition accounts for 67.2 to 79.5% of total costs across all tested CONOPS. Operating costs contributes between 19.7 and 30.9% to total cost and ordnance accounts for 0.8 to 3.2% of total costs. Based on these results, the cost due to BLUE aircraft attrition is the most significant influence on the CONOPS MOP.

Table 19. CONOPS MOP and Cost Factors

CONOPS	Aircraft		**MOP** Mean Cost per RED Kill	Mean RED kills	Mean Total Cost	Mean BLUE Attrition Cost	Mean Operating Cost	Mean Ordnance Cost
	Type	#	$M FY16		$M FY16	$M FY16	$M FY16	$M FY16
3	MH-60S RQ-21A	4 6	2.0	19.95	40.2	27.0 (67.2%)	12.4 (30.9%)	0.8 (1.9%)
4	MQ-8C RQ-21A	3 9	2.4	19.81	47.1	32.6 (69.4%)	13.7 (29.1%)	0.8 (1.5%)
2B	MH-60S	6	3.2	19.95	64.6	45.3 (70.0%)	18.5 (28.7%)	0.8 (1.3%)
1B	MH-60S	6	3.3	19.97	65.7	45.0 (68.5%)	18.6 (28.3%)	2.1 (3.2%)
2A	MH-60S MQ-8C	3 3	4.9	19.88	97.8	77.7 (79.5%)	19.3 (19.7%)	0.8 (0.8%)
1A	MH-60S MQ-8C	3 3	5.0	19.85	99.9	77.1 (77.2%)	20.7 (20.7%)	2.1 (2.1%)

a. CONOP 1A—MH-60S (HELLFIRE) and MQ-8C

With a mean cost per kill of 5.0 $M FY16 and in the 2000 replications a maximum cost per kill of 18.9 and minimum of 1.2 $M the performance of CONOPS 1A ranks last among all tested aircraft configurations. Simulation of CONOPS 1A produced the highest average cost per kill and the second lowest value for the mean number of RED killed. The inability for unarmed MQ-8C to destroy RED, combined with the high APUC for all aircraft operated in the CONOPS resulted in a 286% increase in mean BLUE attrition costs and a 0.5% decrease in mean number of RED killed compared to the best performing CONOPS. CONOPS 1A also suffers the second highest mean BLUE attrition cost 77.1 $M FY16 despite a moderate average of 2.5 BLUE losses from RED weapons engagements due to an average aircraft APUC of 28 $M FY16. Figure 16 depicts the distribution of BLUE kills for CONOPS 1A. 98.7% of the CONOPS 1A simulations resulted in a cost per RED kill of less than 10.0 $M FY16. Figure 17 depicts the distribution of the cost per RED kill below 10 $M FY16 for CONOPS 1A.

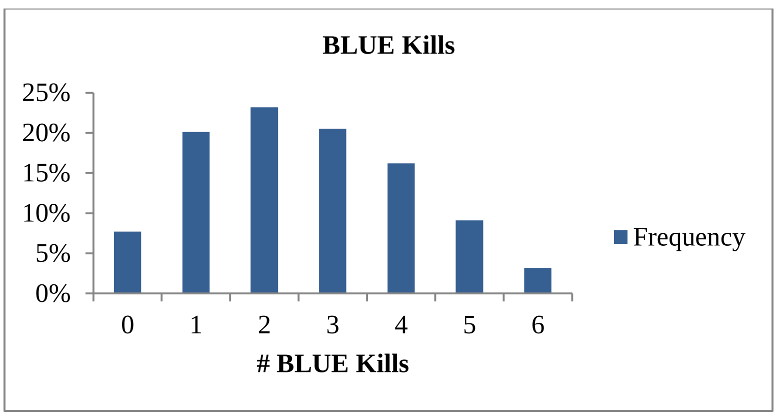

Figure 16. CONOPS 1A: BLUE Kills

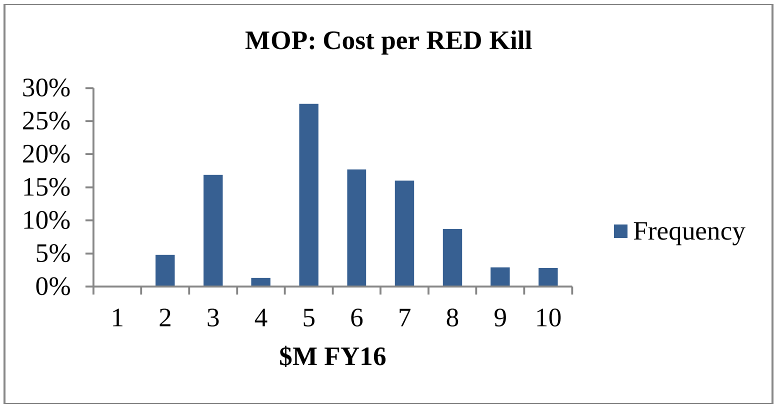

Figure 17. CONOPS 1A Cost per Red Kill

b. *CONOPS 1B—MH-60S (HELLFIRE)*

CONOPS 1B achieved a cost per RED kill with a mean value of 3.3 $M FY16, maximum cost per kill value of 11.1 $M and minimum of 0.9 $M. CONOPS 1B's inclusion of only MH-60S significantly affects the cost per RED kill. We analyzed the cost per RED kill against the distribution of BLUE kills for CONOPS 1B (Figure 18) and determined that the cost per RED kill increases incrementally with each BLUE aircraft loss. 23% of the simulated runs resulted in zero BLUE aircraft losses and a mean cost per RED kill of approximately 1.0 $M FY16. 32% resulted in one BLUE loss and a mean cost per kill of approximately 2.5 $M and 23% resulted in two BLUE losses and a mean cost per kill of approximately 4.0 $M FY16. 99.4% of all simulations resulted in a cost per RED kill less than 10 $M FY16.

The incorporation of only MH-60S in CONOPS 1B resulted in a reduction of BLUE aircraft losses. The MH-60S ability to execute defensive maneuvering, onboard countermeasures and greater system redundancy results in a reduced attrition rate due to RED weapons engagements compared to the studied unmanned aircraft. Simulation of CONOPS 1B yielded an average of 1.6 BLUE losses due to RED weapons. Despite the reduced attrition, an average APUC of 28.5 $M FY16 limits the ability to achieve a low cost per RED kill. Figure 19 depicts the distribution of the cost per RED kill for CONOPS 1B.

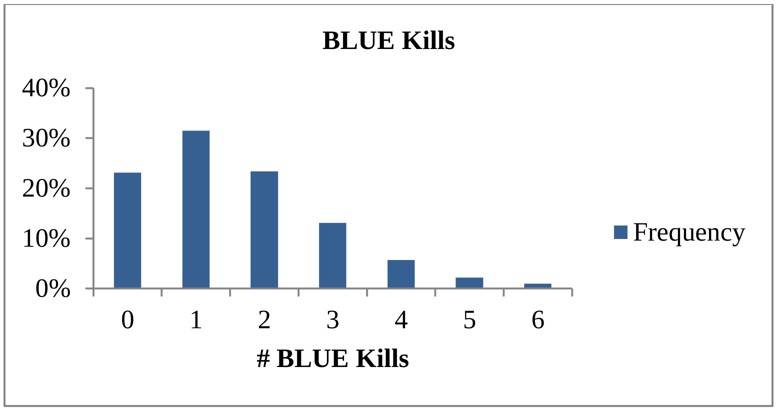

Figure 18. CONOPS 1B: BLUE Kills

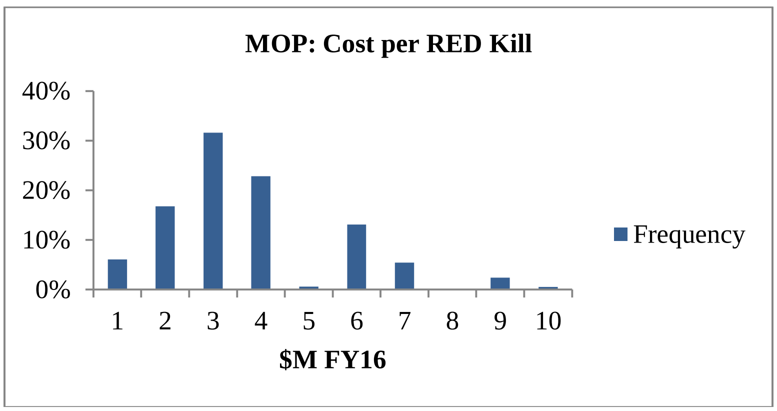

Figure 19. CONOPS 1B Cost per RED Kill

c. CONOPS 2A—MH-60S (APKWS-II) and MQ-8C (APKWS-II)

The cost per RED kill of CONOPS 2A demonstrates the potential impact of future armed MQ-8C. Equipped with APKWS-II, the MH-60S and MQ-8C in CONOPS 2A resulted in a mean cost per RED kill of 4.9 $M FY16, a maximum of 11.5 $M FY16 and a minimum of 1.2 $M. These values represent a 2.0% percent reduction in the mean cost per kill and a 39.2% reduction in the maximum cost per kill compared to CONOPS 1A with unarmed MQ-8C aircraft. The ability for MQ-8C aircraft to destroy RED threats, results in fewer uncontested BLUE-RED engagements and a 0.2% increase in the mean number of RED killed. With the increased weapon engagements CONOPS 2A suffers a 4.0% higher mean number of BLUE kills than CONOPS 1A. The BLUE-RED weapons engagements of MQ-8C result in a higher RED probability of kill versus BLUE and the subsequent increase in the number of mean BLUE kills. Figure 20 depicts the distribution of CONOPS 2A BLUE kills. 99.0% of simulation replications resulted in a cost per RED kill of less than 10 $M FY16. Figure 21 depicts the distribution of cost per RED kill for CONOPS 2A.

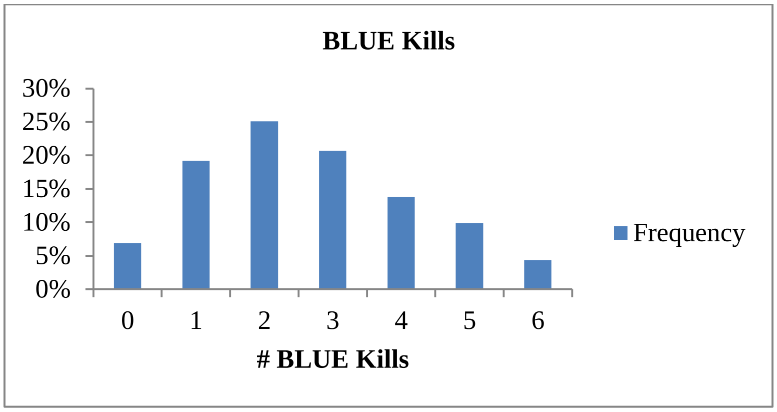

Figure 20. CONOPS 2A BLUE Kills

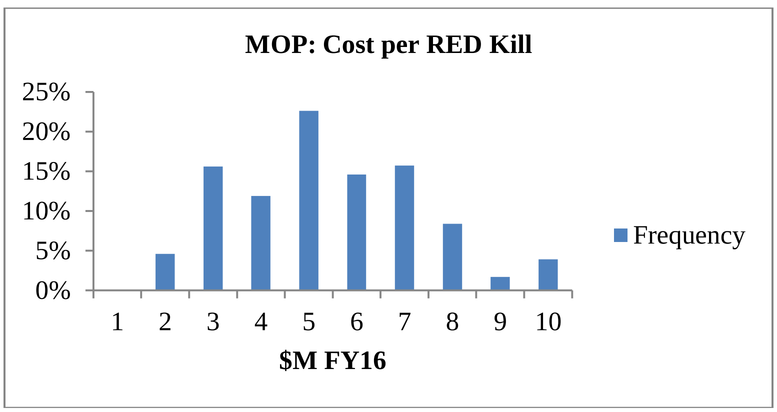

Figure 21. CONOPS 2A Cost per RED Kill

d. CONOPS 2B–MH-60S (APKWS-II)

Through analysis of the CONOPS 2B MOP, we determine the value of the APKWS-II weapon system for the MH-60S. CONOPS 2B achieved a mean cost per RED kill of 3.2 $M FY16, a 3.0% reduction from that of CONOPS 1B composed of MH-60S equipped with HELLFIRE missiles. The replacement of HELLFIREs with APKWS-II results in a 61.9% reduction in mean expended ordnance cost (as presented in Table 20).

Table 20. CONOPS Ordnance Expenditure Costs

CONOPS	Aircraft		Ordnance	
	Type	#	Type	Mean Expended Cost ($M FY16)
1A	MH-60S	3	HELLFIRE	2.1
	MQ-8C	3	N/A	
1B	MH-60S	6	HELLFIRE	2.1
2A	MH-60S	3	APKWS	0.8
	MQ-8C	3	APKWS	
2B	MH-60S	6	APKWS	0.8
3	MH-60S	4	APKWS	0.8
	RQ-21A	6	N/A	
4	MQ-8C	3	APKWS	0.8
	RQ-21A	9	N/A	

CONOPS 2B results in a maximum mean cost per RED kill of 11.1 and a minimum mean cost per kill of 0.8 $M FY16. Figure 22 displays distribution of CONOPS 2B BLUE kills. Based on the inclusion of only MH-60S aircraft, CONOPS 2B demonstrates an incremental increase in mean cost per RED kill similar to the behavior of CONOPS 1B. 99.0% of all simulations resulted in a cost per RED kill of under 10 $M FY16. Figure 23 depicts the cost per RED kill for CONOPS 2B.

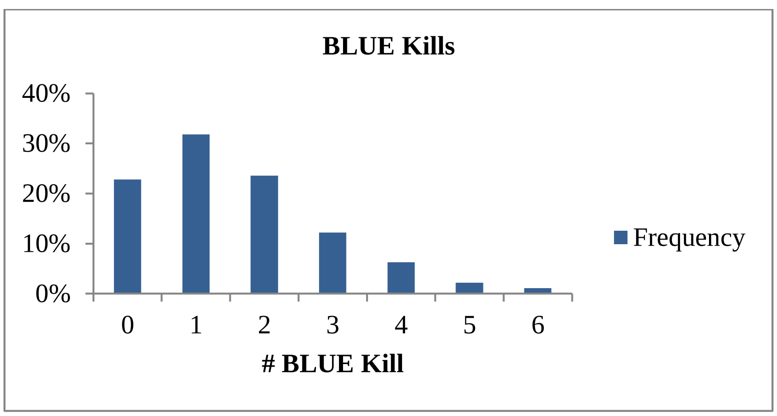

Figure 22. CONOPS 2B BLUE Kills

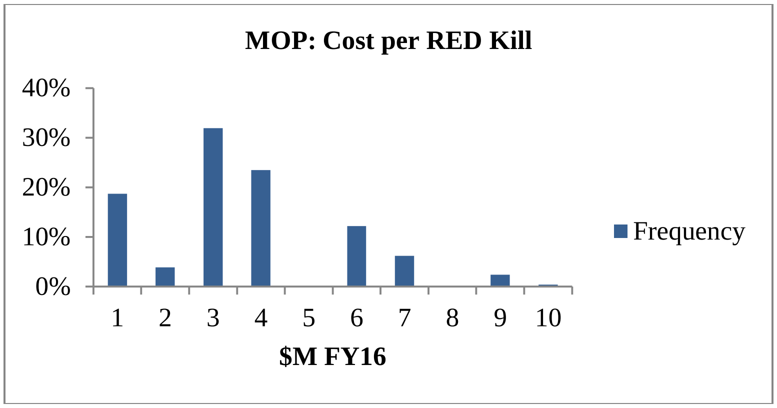

Figure 23. CONOPS 2B Cost per RED Kill

e. CONOPS 3

CONOPS 3 is the first modeled aircraft configuration that includes the RQ-21A. With a mean cost per RED kill of 2.0 $M FY16, maximum of 9.7 $M and minimum cost per kill of 0.7 $M FY16 CONOPS 3 outperforms all other aircraft configurations in the study. CONOPS 3 is the clearest illustration of the effect of BLUE attrition on cost per RED kill. Simulation of CONOPS 3 results in an average value of 4.0 BLUE kills, the study's second highest value. Despite approximately twice the mean number of BLUE kills of other CONOPS, the RQ-21A APUC of 4.3 $M FY16 is 88% lower than other evaluated aircraft and results in a study low BLUE mean attrition cost of 27.0 $M FY16. The CONOPS pairing of RQ-21A and MH-60S achieves an average of 19.95 RED kills. Figure 24 presents the distribution of BLUE kills for CONOPS 3. 100% of simulations resulted in a mean cost per RED kill below 10 $M FY16. Figure 25 depicts the distribution of the cost per RED kill for CONOPS 3.

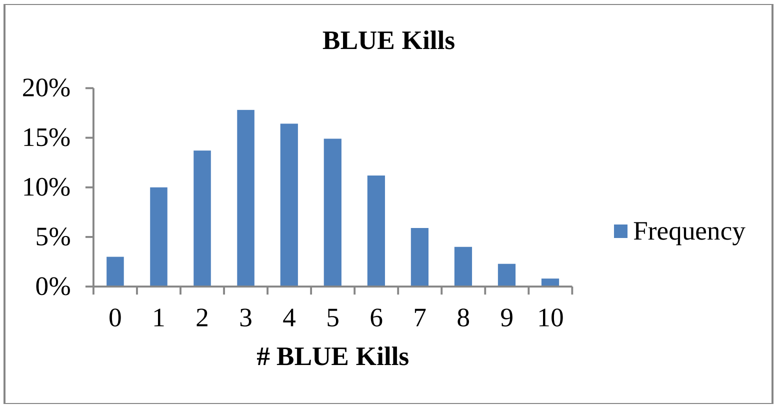

Figure 24. CONOPS 3 BLUE Kills

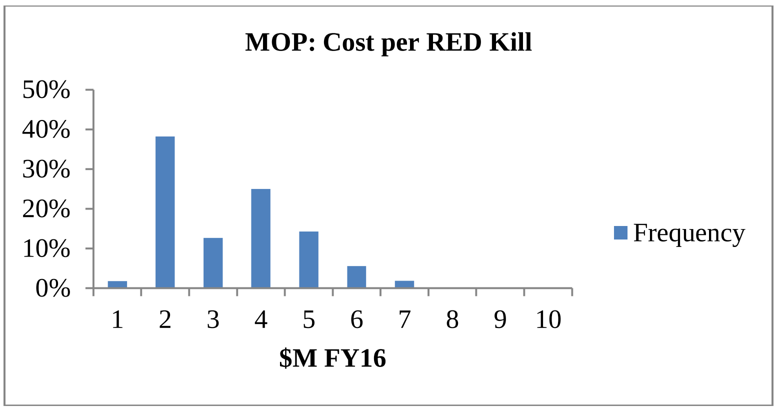

Figure 25. CONOPS 3 Cost per RED Kill

f. CONOPS 4–MQ-8C (APKWS-II) and RQ-21A

Composed of MQ-8C and RQ-21A, CONOPS 4 is the only fully unmanned aircraft configuration modeled. CONOPS 4 resulted in an average cost per RED kill of 2.4 $M FY16, a maximum of 10.6 $M, and a minimum cost per kill of 1.9 $M FY16. Composed of 75% RQ-21A, the mean cost per RED kill of CONOPS 4 benefits the study's lowest average aircraft APUC of 10.1 $M. With an average aircraft APUC 27.7% lower than the second lowest value of 13.9 $M for CONOPS 3, CONOPS 2 achieves the second lowest mean cost per RED kill despite an average of 4.8 BLUE kills. Figure 26 presents the CONOPS 4 distribution of BLUE kills. 100% of simulations result in a cost per RED kill less than 10 $M FY16. Figure 27 depicts the distribution of the cost per RED kill for CONOPS 4.

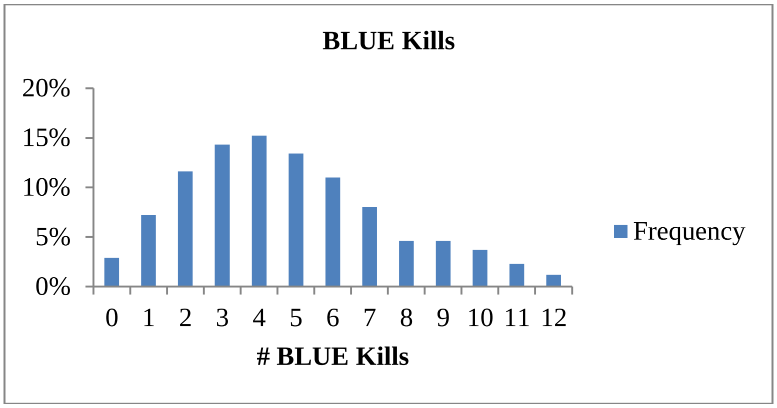

Figure 26. CONOPS 4 BLUE Kills

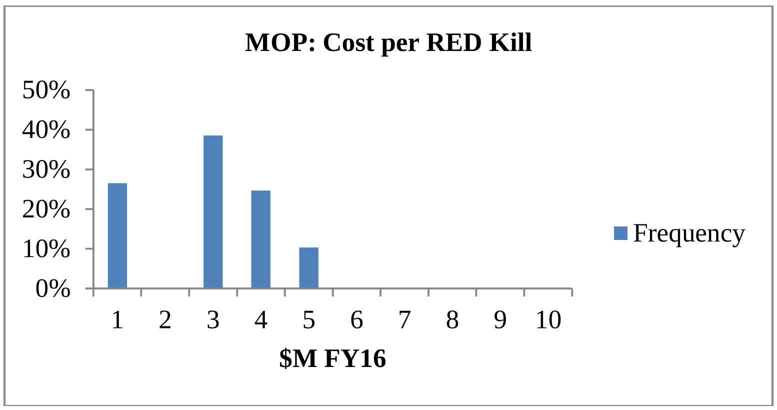

Figure 27. CONOPS 4 Cost per RED Kill

2. MOE #1: RED Kills

The RED kills measure of effectiveness represents the ability of a CONOPS to destroy RED forces over a finite time period. To determine RED kills, we conducted 2000 simulations of each CONOPS for a duration of 30 days and measured the quantity of RED remaining from an initial force of 20. The mean value for RED kills ranged from 19.97 to 19.81. Despite the small 0.8% difference between the most effective and least effective CONOPS, analysis of the simulation-generated data determined that CONOPS quantity and percentage of ordnance carrying aircraft and BLUE aircraft survivability most significantly affect the number of RED kills. Table 21 presents RED kill data for the evaluated CONOPS ranked in decreasing order of RED kills.

Table 21. MOE#1: RED Kills

<table>
<tr><th rowspan="2">CONOPS</th><th colspan="2">Aircraft</th><th rowspan="2">% Aircraft Armed</th><th rowspan="2"># Armed Aircraft</th><th rowspan="2">Mean BLUE Kills</th><th rowspan="2">MOE #1 Mean RED kills</th><th rowspan="2">100% RED Kill Rate</th><th rowspan="2">Minimum % RED Killed (in 2000 simulation replication)</th></tr>
<tr><th>Type</th><th>#</th></tr>
<tr><td>2B</td><td>MH-60S</td><td>6</td><td>100%</td><td>6</td><td>1.6</td><td>19.97</td><td>98.4%</td><td>80%</td></tr>
<tr><td>1B</td><td>MH-60S</td><td>6</td><td>100%</td><td>6</td><td>1.6</td><td>19.97</td><td>98.3%</td><td>80%</td></tr>
<tr><td rowspan="2">3</td><td>MH-60S</td><td>4</td><td rowspan="2">40%</td><td rowspan="2">4</td><td rowspan="2">4.0</td><td rowspan="2">19.95</td><td rowspan="2">97.4%</td><td rowspan="2">60%</td></tr>
<tr><td>RQ-21A</td><td>6</td></tr>
<tr><td rowspan="2">2A</td><td>MH-60S</td><td>3</td><td rowspan="2">100%</td><td rowspan="2">6</td><td rowspan="2">2.6</td><td rowspan="2">19.88</td><td rowspan="2">93.1%</td><td rowspan="2">75%</td></tr>
<tr><td>MQ-8C</td><td>3</td></tr>
<tr><td rowspan="2">1A</td><td>MH-60S</td><td>3</td><td rowspan="2">50%</td><td rowspan="2">3</td><td rowspan="2">2.6</td><td rowspan="2">19.85</td><td rowspan="2">92.6%</td><td rowspan="2">45%</td></tr>
<tr><td>MQ-8C</td><td>3</td></tr>
<tr><td rowspan="2">4</td><td>MQ-8C</td><td>3</td><td rowspan="2">25%</td><td rowspan="2">3</td><td rowspan="2">4.8</td><td rowspan="2">19.81</td><td rowspan="2">92.8%</td><td rowspan="2">40%</td></tr>
<tr><td>RQ-21A</td><td>9</td></tr>
</table>

a. Ordnance Carrying Aircraft

The study determined that the CONOPS quantity of ordnance carrying aircraft contributed to RED kill performance. Within the study the number of ordnance carrying aircraft varied from three (CONOPS 1A and 4) to six (CONOPS 1B, 2A and 2B). All CONOPS composed of greater than four ordnance carrying aircraft destroyed greater than an average of 19.88 of 20 RED threats. Simulation results indicate that for an operational duration of 30 days, quantities below four armed aircraft, as in CONOPS 1A and 4, there is a moderate reduction in BLUE's ability to destroy RED forces. An improvement in RED kill performance due to an increased quantity of BLUE armed aircraft results from a higher percentage of BLUE and RED interactions that include BLUE weapons engagements and subsequent RED kills.

b. Percentage of Ordnance Carrying Aircraft

In conjunction with an increased quantity of BLUE armed aircraft, the percentage of armed aircraft within a CONOPS also affects number of RED killed. Composed of 100% armed aircraft, CONOPS 1B, 2A, and 2B resulted in three of the top four mean kill rates (RED killed/20). Conversely, CONOPS 1A and 4, composed of only 50% and 25% armed aircraft recorded the two lowest values for average RED kills. As RED forces engage and destroy BLUE aircraft at random, a higher percentage of BLUE armed aircraft improves the likelihood that remaining BLUE aircraft are capable of weapons employment against RED threats.

c. BLUE Survivability

CONOPS 1B and 2B demonstrate the effect of BLUE attrition on the number of RED killed. CONOPS 1B and 2B with study-low mean BLUE kill quantities of 1.6 aircraft achieved the highest average number of RED kills. Increased BLUE survivability allows BLUE aircraft to execute a higher number of kill chains and achieve an increased number of RED kills. Increased BLUE attrition, as demonstrated by CONOPS 1A and 4, resulted in a lower number of RED kills.

d. Probability of RED Annihilation and Minimum Percent RED Killed

The study determined that an increased quantity, percentage and survivability of BLUE armed aircraft result in a higher probability of destroying all RED and increase the minimum percentage of RED killed in the simulation replications. Over 98% of all CONOPS 1B and 2B simulations resulted in the annihilation of RED forces and a minimum of 80% of RED forces killed in the replications.

3. MOE #2: Time Till 50% RED Attrition

The time until 50% RED attrition measures the ability of BLUE forces to eliminate the combat effectiveness of RED forces. 2000 simulations of each CONOPS resulted in a range of 4.5 to 17.0 hours. Analysis of the results determined that in-flight ordnance availability and the ordnance capacity of the aircraft configurations affect the performance of the CONOPS. While the study individually addresses these factors, the simulation results indicate an inter-dependency and collective influence of the factors on the time until 50% RED attrition. Table 22 presents the mean values of time until 50% RED attrition for all successful attempts and associated metrics ranked in descending order of time until 50% RED attrition.

Table 22. MOE #2: Time Until 50% RED Attrition

CONOPS	Aircraft		In-flight Ordnance Availability	**MOE #2 Mean Time till 50% RED Attrition**	Failures to Achieve 50%	Replication Maximum Time Until 50% RED Attrition	Replication Minimum Time Until 50% RED Attrition
	Type	#	Hours	Hours	% of 2000 simulations	Hours	Hours
4	MQ-8C	3	36	4.5	0.2%	51.4	2.1
	RQ-21A	9					
3	MH-60S	4	14	4.7	0.0%	48.8	2.1
	RQ-21A	6					
2B	MH-60S	6	21	5.2	0.0%	33.7	2.1
1B	MH-60S	6	21	5.2	0.0%	36.7	2.1
2A	MH-60S	3	57	6.1	0.0%	121.3	2.0
	MQ-8C	3					
1A	MH-60S	3	10.5	17.0	0.2%	153.0	3.5
	MQ-8C	3					

a. Ordnance Carrying Aircraft

An increased quantity of BLUE armed aircraft reduces the mean time until 50% RED attrition. Simulation of CONOPS 3, 4, 2B, 2A and 1B resulted in an average time until 50% attrition of less than 5.0 hours, or within the first day of flight operations. Configured with a minimum of three armed aircraft each CONOPS maintained the ability to expeditiously prosecute RED targets upon classification. A distinct disparity is observed for CONOPS 1A with a mean time until 50% RED attrition of 17.0 hours due to its low in-flight ordnance availability, determined by the quantity and average sortie duration of the CONOPS armed aircraft.

b. In-flight Ordnance Availability

Despite being equipped with three BLUE armed aircraft, CONOPS 1A achieved a study-low mean time until 50% RED attrition of 17.0 hours due a lack in-flight ordnance availability. Quantity and average sortie length of ordnance carrying aircraft determine in-flight ordnance availability. Configured with three armed MH-60S and an average aircraft sortie length of 3.5 hours, CONOPS 1A generates an in-flight ordnance availability of 10.5 hours, compared to the 21 hours of ordnance availability provided by the CONOPS 1B six MH-60S. The reduced ordnance availability increases the duration between BLUE weapon engagements and the mean time until 50% attrition. Configured with nine RQ-21s, CONOPS 4 achieves a mean time until 50% attrition of 4.5 hours due to significantly decreased surveillance durations based on the search effort contributed by the RQ-21s.

c. Failure to Achieve 50% RED Attrition

All CONOPS resulted in high rates of success for achievement of 50% RED attrition with all CONOPS succeeding in over 99% of simulations. The small percentage of failures experienced by CONOPS 1A and 4 resulted in replications where BLUE casualties affected all ordnance carrying aircraft. Increased quantities of BLUE armed aircraft prevented similar behavior in the other studied CONOPS.

d. Maximum and Minimum 50% RED Attrition Times

Simulation of all CONOPS resulted in comparable minimum times until 50% RED attrition with a maximum value of 3.5 hours for CONOPS 1 and minimum value of 2.0 hours for CONOPS 2A. Minimum 50% RED attrition times represent simulation runs without BLUE attrition and enable full aircraft and ordnance availability to reduce the time required for kill chain execution.

The CONOPS maximum times until 50% RED attrition vary significantly. With the highest quantities of aircraft, CONOPS 1B and 2B resulted in the lowest simulation replication maximum 50% attrition time of less than 37 hours. Configured with MH-60S the CONOPS benefit from the highest percentage of armed aircraft and the most survivable aircraft.

Simulation of CONOPS 3 and 4 resulted in maximum 50% RED attrition times of 48.8 and 51.4 hours, respectively. Configured with 10 and 12 aircraft, CONOPS 3 and 4 utilize the sorties generated by the RQ-21s to rapidly locate and classify RED threats and therefore more effectively employ the armed BLUE aircraft in target prosecution.

Configured with three armed MH-60S, a study-wide low value for in-flight ordnance availability and a significantly increased requirement for BLUE aircraft recovery and refueling, CONOPS 1A resulted in the highest replication maximum time until 50% RED attrition. One in 2000 simulations of CONOPS 1A resulted in the loss of two BLUE armed aircraft and the replication maximum 50% RED attrition time of 153.0 hours.

4. MOE #3: Mean BLUE detection time

BLUE detection time is a measurement of the effectiveness of a CONOPS to detect both neutral and RED surface contacts. Lower detection time results in more expedient classification of RED threats and therefore the accelerated engagement and destruction of RED forces from the AO. We conduct 2000 simulations per CONOPS to achieve a BLUE detection rate ranging from one detection every 0.6 to 1.1 hours across all evaluated CONOPS. Analysis of the simulation data discovered average search velocity and quantity of BLUE aircraft have the most significant influence on mean BLUE detection time. Table 23 presents the mean, maximum and minimum BLUE detection times for all studied CONOPS.

Table 23. MOE #3: BLUE Detection Time

CONOPS	Aircraft		Average Aircraft Search Speed	**MOE #3 Mean BLUE Detection Time**	Replication Maximum BLUE Detection Time	Replication Minimum BLUE Detection Time
	Type	#	Kts	Hours	Hours	Hours
2B	MH-60S	6	75	0.5	1.1	0.3
1B	MH-60S	6	75	0.5	1.1	0.3
2A	MH-60S	3	67.5	0.7	1.5	0.4
	MQ-8C	3				
3	MH-60S	4	63	0.8	1.9	0.3
	RQ-21A	6				
4	MQ-8C	3	56.3	0.9	2.3	0.2
	RQ-21A	9				
1A	MH-60S	3	67.5	1.1	2.4	0.4
	MQ-8C	3				

a. Average Search Velocity

CONOPS 1B and 2B demonstrate the effect of average search velocity on mean BLUE detection time. With a study-high average search velocity of 75 knots, CONOPS 1B and 2B generate increased search effort and a reduced mean BLUE detection time. With a reduced average search speed of 67.5 knots, CONOPS 2A achieved an average detection time of 0.7 hours.

b. Aircraft Quantity

Simulation of CONOPS 3 and 4, resulted in a mean detection time of 0.8 and 0.9 hours, respectively, a 33.3% decline from the performance of the best CONOPS. Configured with 10 and 12 aircraft, CONOPS 3 and 4 generated sufficient cumulative search effort despite an approximate 17% reduction in average search speed from CONOPS 1B and 2B. CONOPS 1A significantly underperformed all other CONOPS. Affected by a study-wide high average BLUE attrition rate of 46.2%, CONOPS 1A generated the minimum cumulative search effort and resulted in a mean BLUE detection time of 1.1 hours.

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V. EXPERIMENTATION AND SENSITIVITY ANALYSIS

A. INTRODUCTION

Based on the impact of BLUE aircraft attrition, we analyzed the simulation results to determine the kill chain events in which BLUE aircraft demonstrate the most significant vulnerability to RED weapons engagements. We determined that 72% percent of BLUE aircraft losses due to RED weapon engagements occur during the BLUE CLASSIFICATION event and 28% occur when BLUE aircraft maintain classification altitudes and slant ranges in the BLUE WEAPON ENGAGEMENT event. The CLASSIFICATION event corresponds with the minimum kill chain flight-profile altitudes and slant ranges due to the imagery requirements in support of RED vessel classification and the greatest BLUE exposure to the RED weapons envelope. As the BLUE aircraft sensor capabilities determine the CLASSIFICATION altitude and slant ranges, we experimented with improved sensor capabilities and the subsequent increases in CLASSIFICATION altitudes and slant ranges in order to determine the impact on BLUE aircraft attrition and cost per RED kill.

B. METHODOLOGY

Sensor capability improvements affect BLUE survivability through an increased distance between the BLUE aircraft and the RED weapons envelope and through the reduction in RED's ability to visually detect BLUE. As discussed in Chapter 3 Section G.2.e, RED's ability and time to visual detect BLUE during the classification event is determined by RED's discrete glimpse probability of detection. An increase in BLUE's distance from RED reduces the glimpse probability and increases the RED time to detect BLUE. This improves the likelihood that the BLUE aircraft will classify and engage the RED threat before the RED threat can utilize its weapons against the BLUE aircraft.

In order to calculate the impact of sensor capability improvement on the RED glimpse probability of detection we utilized the U.S. Army Night Vision Integrated Performance Model software (U.S. Army, NV-IPM V1.2) to evaluate adjusted probability of detection values for 10% incremental increases in the classification slant range up to 100% of all studied aircraft. The projected size of the target aircraft affects the rate of RED glimpse probability decrease. As illustrated in Figure 28, the glimpse probabilities of the studied aircraft decrease at varying rates. The largest aircraft, the MH-60S, decreases at the slowest rate. Slightly smaller than the MH-60S, the glimpse probability of the MQ-8C exhibits an increased decay rate. The glimpse probability of the smallest aircraft in the study, the RQ-21A, decreases at a rapid rate as the range from the RED threat increases. Figure 28 displays the calculated RED glimpse probability variations with the sensor capability improvements.

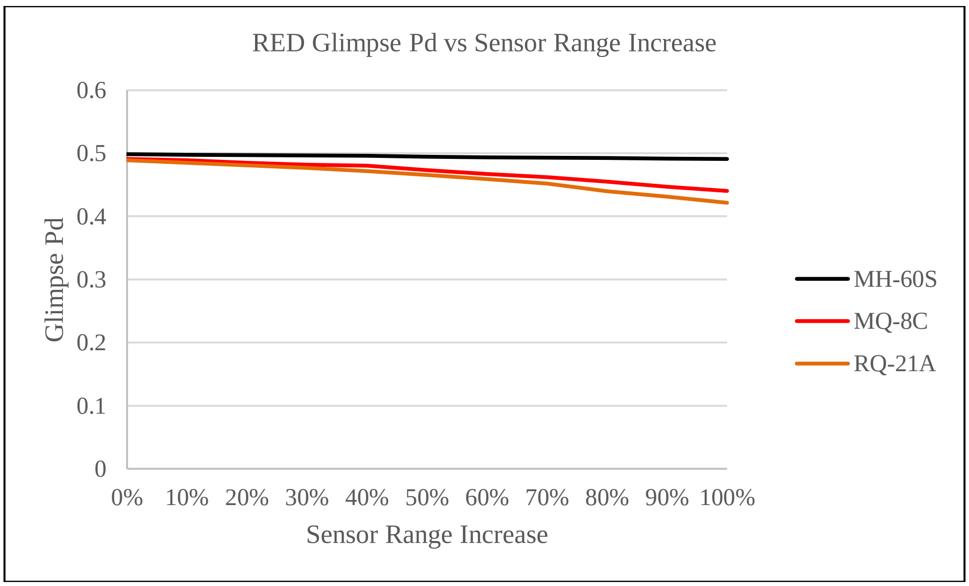

Figure 28. RED Glimpse Probability of Detection versus Sensor Range Increase

Based on the adjusted RED glimpse probability of detection values and increased BLUE classification altitude and slant ranges, we executed 120,000 simulations to collect adjusted cost per RED kill and BLUE kill values for each 10% increment in sensor capability across all six evaluated CONOPS.

C. RESULTS

As presented in Figure 29, incremental sensor range increases result in significant mean cost per RED kill jumps at 10%, 40% and 100% sensor improvements based on reduced BLUE kills. Figure 30, depicts the impact of sensor improvement on the number of BLUE kills for all evaluated CONOPS. CONOPS 3 consistently outperforms all other CONOPS, with the exception of the 10% to 40% sensor improvement range when reduced MQ-8C attrition results in the superior performance of CONOPS 4. This analysis is performed under the assumption that the evaluated sensor improvement are cost-neutral and therefore do not affect the aircraft APUC.

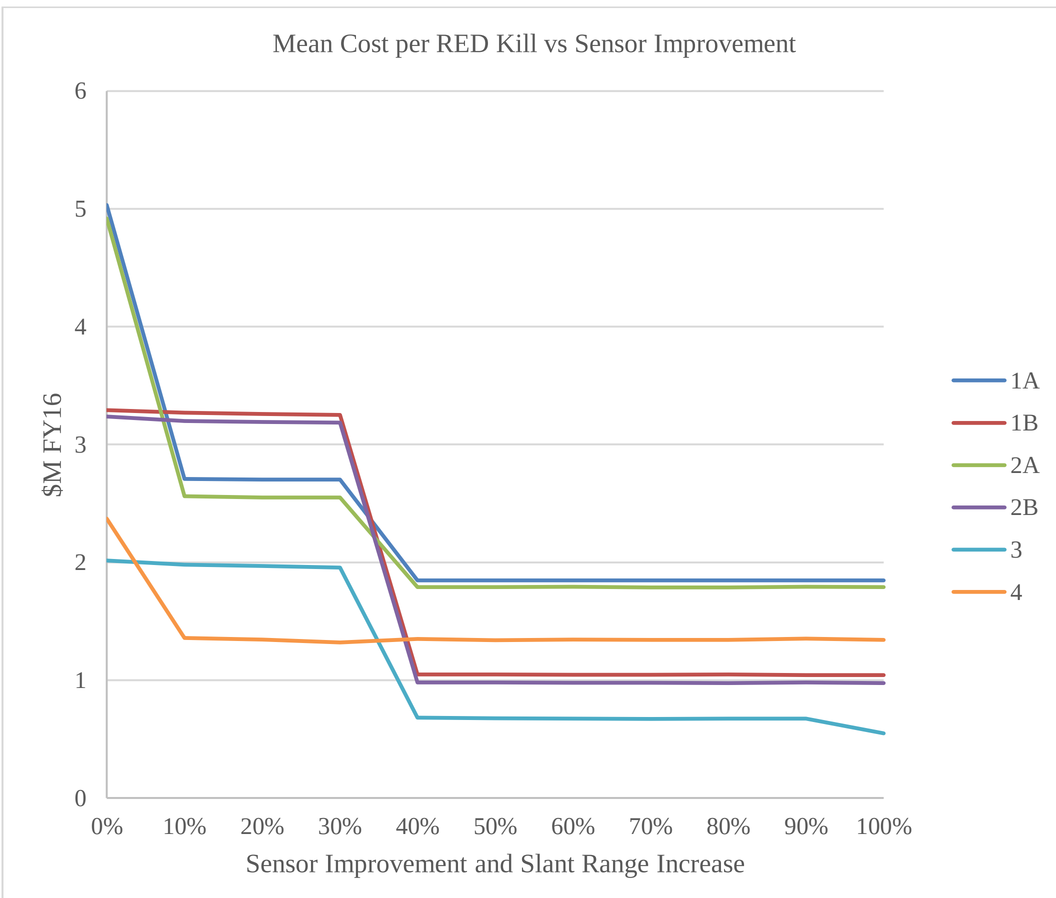

Figure 29. Cost per RED Kill versus Sensor Improvement

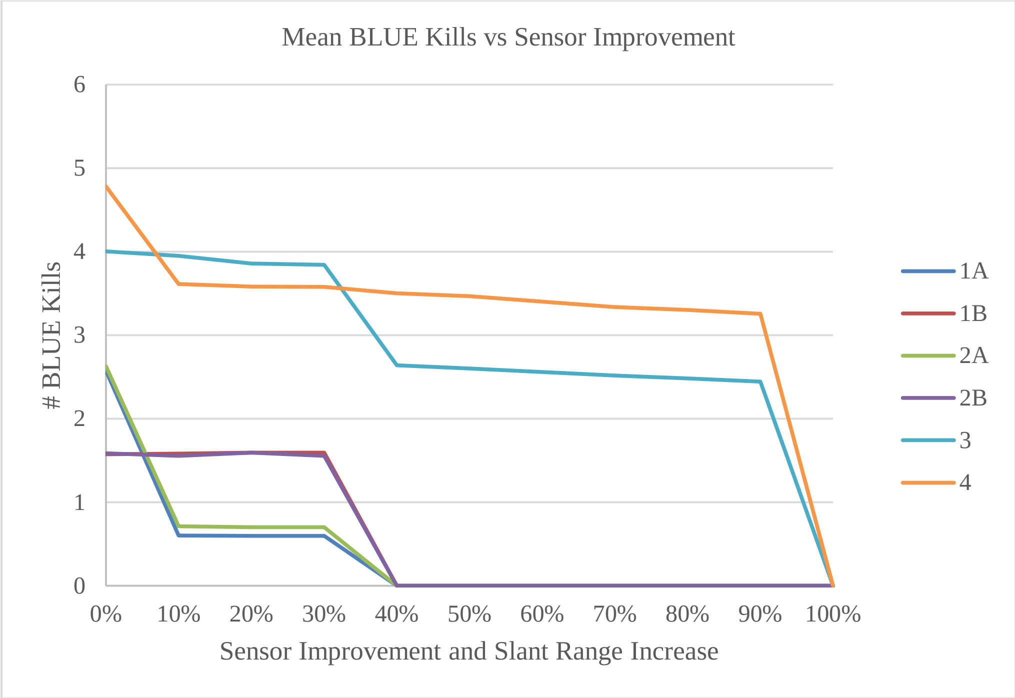

Figure 30. Mean BLUE Kills versus Sensor Improvement

1. 10% Sensor Improvement

The fully unmanned CONOPS 4 delivers the lowest cost per RED kill with a 10% sensor improvement. The 10% increase in sensor capability enables the MQ-8C classification altitude to exceed the RED SAM threat envelope altitude by 120 meters. The altitude separation eliminates the RED weapons exposure of the MQ-8C. All BLUE losses due to RED weapons engagement affect the RQ-21A of CONOPS 4 and result in a BLUE attrition cost 57.7% less than the performance of the next best CONOPS.

The MQ-8C exit from the RED threat envelope combined with moderate decreases in the RED glimpse probability for the RQ-21, result in significantly decreased mean BLUE attrition for CONOPS 1A, 2A and 4. Marginal reductions in RED glimpse probability for MH-60S aircraft result in minimal BLUE attrition and cost per RED kill effects on CONOPS 1B, 2B and 3.

A 10% sensor improvement also marks the first event where BLUE attrition costs no longer dictate cost per RED kill across all CONOPS. In all previous results, BLUE attrition cost constituted the highest percentage of total costs and therefore had the greatest influence on cost per RED kill. A 10% sensor improvement removes the losses of MQ-8 aircraft to RED weapons. This enables the MQ-8 aircraft to execute increased flight hours and generate increased operating costs. As a result, operating costs constitute 52.8% of the total cost for CONOPS 4 Table 24 presents the mean and standard error (SE) for BLUE kill and cost per RED kill for a 10% increase in sensor capability.

Table 24. Cost per RED Kill—10% Sensor Improvement

CONOPS	Aircraft		MOP	**MOP Modified**		Mean BLUE Kills Baseline	Mean BLUE Kills Modified	
	Type	#	Mean Cost per RED Kill ($M FY16)	**Mean Cost per RED Kill ($M FY16)**	SE	# of aircraft	# of aircraft	SE
4	MQ-8C	3	2.4	**1.4**	0.027	4.8	3.6	0.061
	RQ-21A	9						
3	MH-60S	4	2.0	**2.0**	0.044	4.0	4.0	0.069
	RQ-21A	6						
2A	MH-60S	3	4.9	**2.6**	0.044	2.6	0.7	0.024
	MQ-8C	3						
1A	MH-60S	3	5.0	**2.7**	0.041	2.5	0.7	0.022
	MQ-8C	3						
2B	MH-60S	6	3.2	**3.2**	0.066	1.6	1.6	0.045
1B	MH-60S	6	3.3	**3.3**	0.064	1.6	1.6	0.044

2. 40% Sensor Improvement

Simulation with a 40% sensor improvement restored CONOPS 3 as the most efficient aircraft configuration. With the sensor improvement, the MH-60S classification altitude exceeds the RED SAM envelope maximum altitude by 80 meters, eliminates all BLUE kills from CONOPS 1A, 1B, 2A and 2B and removes MH-60S kills from CONOPS 3. The most significant cost per RED kill reduction occurs in CONOPS 1B and 2B due to their percentage of MH-60S aircraft. The 40% sensor improvement reduces the CONOPS 2B and 1B mean cost per RED kill to 0.7 and 1.1 $M FY16, respectively.

Similar to the results with a 10% sensor improvement, the operating and ordnance costs differences of CONOPS 2B and 1A exert a greater influence than BLUE attrition costs in the cost per RED kill calculations. Across all CONOPS, operating costs outweigh attrition costs. Despite remaining RQ-21A losses to RED weapons, CONOPS 3 outperforms CONOPS 1A, 2A, 1B and 2B with no BLUE kills, due to a 27.0% lower operating cost per flight hour for the RQ-21A compared to the average operating cost of the MH-60S and MQ-8C. Table 25 presents the mean and standard error (SE) of the cost per RED kill based on a 40% sensor improvement.

Table 25. Cost per RED Kill—40% Sensor Improvement

CONOPS	Aircraft		**MOP Modified**		Mean BLUE Kills Modified		Mean Operating Cost	
	Type	#	**Mean Cost per RED Kill ($M FY16)**	SE	# of aircraft	SE	$M FY16	SE
3	MH-60S	4	**0.7**	0.006	4.0	0.045	12.5	0.023
	RQ-21A	6						
2B	MH-60S	6	**1.0**	0.005	0	0.0	18.4	0.030
1B	MH-60S	6	**1.1**	0.005	0	0.0	18.4	0.031
4	MQ-8C	3	**1.4**	0.027	4.8	0.059	14.6	0.023
	RQ-21A	9						
2A	MH-60S	3	**1.8**	0.026	0	0.0	23.9	0.024
	MQ-8C	3						
1A	MH-60S	3	**1.8**	0.026	0	0.0	23.8	0.028
	MQ-8C	3						

3. 100% Sensor Improvement

100% sensor improvement marks the final significant change in cost per RED kill. A 100% sensor improvement results in the RQ-21A classification altitude and slant range exceeding the RED SAM envelope maximum altitude and range. This reduction eliminates all BLUE losses due to RED weapons engagements. With the highest in-flight catastrophic failure rate of 1 per 1000 flight hours, the mean cost per RED kill of CONOPS 3 and 4 decrease by only 0.5 and 0.7 percent based on mean BLUE attrition costs between 98% and 50% higher than non-RQ-21 configured CONOPS. Based on the mishap driven attrition cost and eliminate of BLUE kills, sensor improvements in excess of 100% fail to significantly affect the cost per RED kill of the evaluated CONOPS. Table 26 presents the mean and standard error (SE) of the cost per RED kill based on a 100% sensor improvement.

Table 26. Cost per RED Kill—100% Sensor Improvement

CONOPS	Aircraft		**MOP Modified**		Mean BLUE Kills Modified		Mean Mishap Related BLUE Attrition Costs		Mean Operating Cost	
	Type	#	**Mean Cost per RED Kill ($M FY16)**	SE	# of aircraft	SE	$M FY16	SE	$M FY16	SE
3	MH-60S	4	**0.7**	0.004	0	0.0	0.2	0.080	12.4	0.023
	RQ-21A	6								
2B	MH-60S	6	**1.0**	0.005	0	0.0	0.3	0.094	18.4	0.031
1B	MH-60S	6	**1.1**	0.005	0	0.0	0.3	0.094	18.4	0.031
4	MQ-8C	3	**1.3**	0.026	0	0.0	11.5	0.522	14.5	0.023
	RQ-21A	9								
2A	MH-60S	3	**1.8**	0.026	0	0.0	11.1	0.527	23.9	0.024
	MQ-8C	3								
1A	MH-60S	3	**1.8**	0.026	0	0.0	11.0	0.521	23.8	0.028
	MQ-8C	3								

D. SENSOR COST BREAK-EVEN ANALYSIS

Section C demonstrates the effect on sensor improvement on cost per RED kill in the absence of sensor improvement cost influences. In order to account for this cost influence, the study conducted a break-even analysis to determine the cost threshold for the sensor improvement percentages that represent stand-off ranges outside the RED threat envelope for all modeled aircraft. For the purpose of our analysis, CONOPS 2A is selected to evaluate the break-even cost of MQ-8C aircraft, CONOPS 2B for MH-60S aircraft and CONOPS 3 for RQ-21A aircraft.

1. MQ-8C 20% Sensor Improvement

Removal of the MQ-8C from the modeled RED threat requires a 10% sensor improvement. A 10% sensor improvement results in a CONOPS 2A mean cost per RED kill of 2.6 $M FY16 and a mean total cost of 53.4 $M FY16. These values represent a 47.0% reduction in mean cost per RED kill and 43.4% reduction in mean total cost compared to the baseline values of 4.9 $M and 97.8 $M for CONOPS 2A. We determine the break-even cost of the sensor improvement by dividing the total cost savings by the quantity of sensor to be improved.

$$\text{Total Cost Savings} = \text{Total Cost}_{\text{2A Baseline}} - \text{Total Cost}_{\text{2A w/ 10\% improvement}}$$
$$\text{Total Cost Savings} = 97.8\ \$\text{M} - 53.4\ \$\text{M}$$
$$\text{Total Cost Savings} = 44.4\ \$\text{M}$$

We assume that all procured MQ-8C receive the 10% sensor improvement. This results in a requirement for 32 sensor upgrades. We then divide the total cost savings of 44.4 $M by the quantity of sensor improvements and determine a break-even improvement cost of 1.39 $M FY16 per sensor.

2. MH-60S 40% Sensor Improvement

Removal of the MH-60S from the modeled RED threat requires a 40% sensor improvement. A 40% sensor improvement resulted in a CONOPS 2B mean cost per RED kill of 1.0 $M FY16 and a mean total cost of 19.6 $M FY16. These values represent a 68.8% reduction in mean cost per RED kill and 69.7% reduction in mean total cost compared to the baseline values of 3.2 $M and 64.7 $M for CONOPS 2B. We use the previous methodology and determine the break-even cost of the sensor improvement.

$$\text{Total Cost Savings} = \text{Total Cost}_{\text{2B Baseline}} - \text{Total Cost}_{\text{2B w/ 40\% improvement}}$$

$$\text{Total Cost Savings} = 64.7\ \$\text{M} - 19.6\ \$\text{M}$$

$$\text{Total Cost Savings} = 45.1\ \$\text{M}$$

$$\text{Required sensor upgrades} = 275$$

$$\text{Break-even cost} = 0.16\ \$\text{M FY16}$$

3. RQ-21A 100% Sensor Improvement

Removal of the RQ-21A from the modeled RED threat requires a 100% sensor improvement. A 100% sensor improvement resulted in a CONOPS 3 mean cost per RED kill of 0.7 $M FY16 and a mean total cost of 13.4 $M FY16. These values represent a 65.0% reduction in mean cost per RED kill and 66.7% reduction in mean total cost compared to the baseline values of 2.0 $M and 40.2 $M for CONOPS 3 We use the previous methodology and determine the break-even cost of the sensor improvement.

$$\text{Total Cost Savings} = \text{Total Cost}_{\text{3 Baseline}} - \text{Total Cost}_{\text{3 w/ 100\% improvement}}$$

$$\text{Total Cost Savings} = 40.2\ \$\text{M} - 13.4\ \$\text{M}$$

$$\text{Total Cost Savings} = 26.8\ \$\text{M}$$

$$\text{Required sensor upgrades} = 185$$

$$\text{Break-even cost} = 0.15\ \$\text{M FY16}$$

Based on the determined break-even analysis, we estimate that a MQ-8C sensor improvement break-even cost of 1.39 $M is greater than the anticipated sensor cost and therefore results in an overall cost saving. Conversely, we estimate that the MH-60S sensor improvement break-even cost of 0.16 $M and the RQ-21A cost of 0.15 $M are less than anticipated sensor costs and therefore should not be implemented.

While these values and calculations are only valid for the RED threat modeled, its weapons envelope and the associated effects on BLUE attrition due to sensor capability changes, it provides a methodology for future inclusion in the cost justification for future aircraft sensor upgrades.

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VI. CONCLUSIONS

We simulated four CONOPS and six aircraft configurations to test the effectiveness of manned and unmanned aircraft in the execution of FAC / FIAC ASUW kill chains. Through the post simulation measurement of four key metrics, cost per RED kill, number of RED destroyed, time until 50% attrition of RED forces and average BLUE detection time we ranked the performance of the CONOPS. Table 27 presents the MOP, MOEs and the CONOPS relative performance rankings (lower numbers represent improved performance relative to the other CONOPS).

Table 27. CONOPS Overall Ranking

CONOPS	Aircraft		**MOP**	**MOE #1**	**MOE #2**	**MOE #3**
	Type	#	Mean Cost per RED Kill ($M FY16)	Mean RED Kills	Mean Time till 50% RED Attrition (Hours)	Mean BLUE Detection Time (Hours)
1A	MH-60S	3	6	4	5	5
	MQ-8C	3				
1B	MH-60S	6	3	**1**	3	**1**
2A	MH-60S	3	5	3	4	2
	MQ-8C	3				
2B	MH-60S	6	2	**1**	3	**1**
3	MH-60S	4	**1**	2	2	3
	RQ-21A	6				
4	MQ-8C	3	4	5	**1**	4
	RQ-21A	9				

A. FINDINGS

Based on the simulation results we conclude that the composite manned and unmanned aircraft configuration CONOPS 3 outperforms all other evaluated CONOPS and aircraft configurations. Composed of four MH-60S and six RQ-21A, CONOPS 3 achieved study-wide best results in mean cost per RED kill by 13% when compared to the next best performance of CONOPS 2B. Additionally, CONOPS 3 ranked second in two of the measures of effectiveness and ranked no lower than third in any performance metric. CONOPS 1B and 2B perform well in all key metrics but result in a 38.5% increased cost per RED kill compared to CONOPS 3. Composed of only three armed aircraft with the third highest average aircraft APUC, CONOPS 1A underperformed in all key metrics. While the ranking of the CONOPS provides an indication of preferred aircraft configuration, simulation results determined that no singular factor is the sole determinant of performance. We present the most significant factors supported by the post simulation analysis.

1. BLUE Survivability

Simulation results indicate that BLUE survivability effects FAC / FIAC ASUW kill chain effectiveness when all BLUE aircraft are at risk to RED weapons. CONOPS 2B and 1B consistently outperformed all other evaluated CONOPS in terms of BLUE attrition due to RED weapons engagements. The increased survivability of the MH-60S aircraft compared to the RQ-21A and MQ-8C resulted in 17.8% reduction in mean BLUE kills compared to CONOPS with manned and unmanned aircraft and a 45.6% reduction compared to CONOPS with only unmanned aircraft. This reduction in BLUE aircraft attrition limits attrition costs and preserves the capability to destroy RED forces.

2. Aircraft APUC

The employment of low cost aircraft improves cost per RED kill performance. Despite the study-wide second highest number of mean BLUE kills, configured with six RQ-21A CONOPS 3 achieves a mean cost per RED kill 17% lower than any other evaluated CONOPS or aircraft configuration. With a mean APUC 84.4% less than the other modeled aircraft, RQ-21A losses result in a mean attrition cost 35.8% less than the average attrition cost across all other studied CONOPS.

3. Sortie Duration

Increased BLUE aircraft sortie duration decreases the time required to attrite enemy forces. Despite the superior performance of manned aircraft configured CONOPS in most performance categories, the limited sortie duration and resulting increased requirement for recoveries and post-flight maintenance negatively impacts the ability for CONOPS 1B and 2B to achieve 50% RED attrition. With an average aircraft sortie length of 3.5 hours, CONOPS 1B and 2B require an average of 37 recoveries per aircraft compared to 23.5 recoveries per aircraft for the composite CONOPS and 23.7 for the unmanned CONOPS during the simulation of a 30-day ASUW operation. This increased demand for recoveries reduces mean executed flight hours by 26% and 65% compared to composite and unmanned only CONOPS, respectively. The decreased flight hours, increases the time to detect, classify and destroy and resulted in approximately a 15% increase in time until 50% RED attrition.

4. Unmanned and Unarmed Aircraft Limitations

The performance of CONOPS 1A demonstrates that small quantities of unarmed unmanned aerial vehicles are ineffective at supporting the execution of ASUW kill chains. Without the ability to prosecute RED threats, unarmed MQ-8C aircraft result in a 283% increase in mean time until 50% RED attrition and a 4% increase in mean cost per RED kill compared to the armed MQ-8C in CONOPS 2A.

Performance limitations created by unarmed aircraft decrease as the quantity of unarmed aircraft increases. Simulation of CONOPS 3 and 4, with 6 and 9 unarmed aircraft respectively, maintain the ability to effectively prosecute RED threats and resulted in study-wide best mean time until 50% RED attrition. The additional unarmed aircraft result in greater resilience to BLUE attrition, generate increased flight hours and maintain an effective lethality to destroy RED threats.

5. Sensor Performance Influence on Total Cost

Sensor capabilities influence FAC/FIAC ASUW kill chain execution effectiveness. Sensitivity analysis determined that with knowledge of the RED weapons capabilities (maximum range and altitude), increases in BLUE sensor capabilities can eliminate BLUE losses due to RED weapon engagements. With the elimination of BLUE kills, operating costs contribute the greatest percentage of total cost and become the most significant factor in cost per RED kill performance.

6. Ordnance Costs and Accuracy

Ordnance costs affect kill chain execution efficiency. Simulation results of CONOPS 1B and 2B indicate that moderate decreases in ordnance per round cost influence cost per RED kill. Equipped with HELLFIRE missiles, CONOPS 1B results in a mean cost per RED kill of 3.3 $M FY16. Simulation of CONOPS 2B equipped with APKWS-II rockets results in a mean cost per RED kill of 3.2 $M FY16. With a 65% less expensive cost per round, the APKWS-II equipped CONOPS 2B produced an ordnance mean cost savings of 1.3 $M FY16

B. FUTURE RESEARCH

While this study provides valuable insight into the effectiveness of manned and unmanned aircraft in the execution of FAC / FIAC ASUW kill chains it is limited by its underlying assumptions and the accuracy of its aircraft sensor performance calculations. We recommend future research and expansion on this study in the following areas in order to develop a complete programmatic and operational planning tool.

- Expand upon the day-light only model implemented within this study through the inclusion of night ASUW operations supported by IR sensors.
- Improve accuracy of results through the validation of notional values utilized in the model as operational use of the evaluated aircraft models increases and additional reliability data becomes available.
- Apply cost estimate relationships to improve the accuracy of sensor improvement break-even analysis.
- Compare study results obtained via SIMIO against other available agent-based simulation software.
- Incorporate geographic specific area of operations and predicted tactical and operational schemes of maneuver to increase the fidelity of the results determined by this study.

APPENDIX A. BLUE AIRCRAFT SENSOR CAPABILITIES

A. EO SENSOR PERFORMANCE PARAMETERS

The study utilizes imagery requirements and sensor parameters to determine sensor sweepwidth and maximum sensor to target altitude (ALT) and slant range (SR). Table 28 presents the baseline sensor parameters at the conclusion of the appendix.

1. Imagery Requirements

National Image Interpretability Rating Scales (NIIRS) values determine imagery requirements based on physical characteristics of the modeled RED target and the estimated resolution requirements for target detection and classification. The study selected a NIIRS value of 4 for detection and 6 for classification. Figures 31 and 32 present the NIIRS scale definitions for the values utilized in the model.

Visible NIIRS
Identify all large fighters by type (e.g., FENCER, FOXBAT, F-15, F-14). Detect the presence of large individual radar antennas (e.g., TALL KING). Identify, by general type, tracked vehicles, field artillery, large river crossing equipment, wheeled vehicles when in groups. Detect an open missile silo door. Determine the shape of the bow (pointed or blunt/rounded) on a medium-sized submarine (e.g., ROMEO, HAN, Type 209, CHARLIE 11, ECHO 11, VICTOR II/III). Identify individual tracks, rail pairs, control towers,

Figure 31. NIIRS 4—Identification. Source: Pike (par. 4)

Visible NIIRS
Distinguish between models of small/medium helicopters (e.g., HELIX A from HELIX B from HELIX C, HIND D from HIND E, HAZE A from HAZE B from HAZE C). Identify the shape of antennas on EW/GCI/ACQ radars as parabolic, parabolic with clipped comers or rectangular. Identify the spare tire on a medium-sized truck. Distinguish between SA-6, SA- I 1, and SA- 17 missile airframes. Identify individual launcher covers (8) of vertically launched SA-N-6 on SLAVA-class vessels. Identify automobiles as

Figure 32. NIIRS 6—Classification. Source: Pike (par. 5)

We convert NIIRS values to ground separable distance (GSD) for use in sensor sweepwidth calculations by a derived equation from the logarithmic regression of published GSD and NIIRS values (Chaput 11.8).

$$\text{GSD(meters)} = e^{\left(\frac{\text{NIIRS}-4.8856}{-1.406}\right)}$$

2. Sensor Sweepwidth Calculations

Table 28 provides the initial values for the sensor parameters obtained from UNCLASSIFIED sources listed in Chapter II.B sections 1–3. Notional values are italicized. The study utilized these values and the derived GSD to determine sensor sweepwidth (SW) for the modeled aircraft.

Table 28. Modeled Aircraft EO Sensor Parameters

Aircraft	**EO Sensor**	**Pixel Pitch (PP)**	**Horizontal Pixels**	**Effective Focal Length (EFL)**
		μm	#	M
MH-60S	Raytheon MTS-A AAS-44C(V)1	*9*	640	*0.07*
MQ-8C	FLIR Brite-Star II	*9*	500	*0.09*
RQ-21A	Hoodtech Alticam AC-10	*9*	640	*0.05*

EO sensor SW formulas and sample calculations for the modeled MH-60S:

Sample calculation for MH-60S with a NIIRS level of 6

$$\text{GSD}_{MH-60S} = e^{\frac{(6-4.8856)}{-1.406}} = 0.45\text{m}$$

$$\text{SW}_y = \text{GSD}_y \times \text{Horizontal Pixels}_y \qquad \text{(Olsen n. pag.)}$$

$$\text{SW}_{MH-60S} = 0.45\text{m} \times 640 = 288.0\text{m}$$

3. Maximum Slant Range (Sensor to Target) Calculations

We determined maximum sensor to target slant range (SR) through varying the sensor to target angle (θ), maintaining GSD requirements, sensor pixel pitch (PP) and under the constraint of maximum aircraft altitude through:

$$SR_y = \frac{GSD \times \cos(90\text{-}\theta)*EFL}{PP} \qquad \text{(Leachtenauer 18)}$$

sample calculation of SR for the MH-60S with GSD of 0.45 m

$$SR_{MH-60S} = \frac{GSD \times \cos(90\text{-}\theta)*EFL}{PP} = \frac{0.45\text{ m} \times \cos(90\text{-}\theta) \times .07\text{m}}{.00009\text{m}}$$

Based on GSD requirements and maximization of aircraft altitude we determined an optimal sensor to target angle of 52.5^o

$$SR_{MH-60S} = \frac{0.45\text{m} \times \cos(90\text{-}52.5) \times .07\text{m}}{.00009\text{m}} = 2776.7\text{m}$$

4. Maximum Altitude (Sensor to Target) Calculations

$$ALT_y = SR_y * \cos(\theta)$$

sample calculation for MH-60S

$$ALT_{MH-60S} = SR_{MH-60S} * \cos(\theta)$$

$$ALT_{MH-60S} = 2776.7\text{m} * \cos(52.5) = 1690.3\text{m}$$

5. Calculated Values for Modeled Aircraft

Table 29. Modeled Aircraft Sensor Performance

Aircraft	Detection Sweepwidth (m)	Detection / SURVEILLANCE					Classification				
		NIIRS	GSD (m)	Θ (degrees)	SR (m)	ALT (m)	NIIRS	GSD (m)	Θ (degrees)	SR (m)	ALT (m)
MH-60S	1203.2	4	1.88	77.5	14276	3090*	6	0.45	52.5	2777	1690
MQ-8C	940.0	4	1.88	73.3	17977	5180*	6	0.45	51.8	3557	2200
RQ-21A	1203.2	4	1.88	59.4	8977	4570*	6	0.45	53.7	2026	1200

* indicates altitude limited by aircraft maximum operational ceiling

APPENDIX B. MODEL COST CALCULATIONS

B. MODELED AIRCRAFT APUC CALCULATIONS

The Joint Inflation Calculator Navy Aircraft procurement index (APN 1506) provides required inflation current year (CY) to current year (CY) indices for adjustment from the aircraft program base year (BY) to FY 2016 dollars utilized in the study (ncca.navy.mil/tools/inflation.cfm). Table 30 provides the FY16 APUC values for the modeled aircraft. Chapter II.B.1-3 provides source information for BY APUC values.

Table 30. Aircraft APUC

Aircraft	APUC	BY	Inflation Index	APUC
	$M		$CY to $CY	$M FY16
MH-60S	21.08	1998	1.35	28.46
MQ-8C	23.29	2006	1.18	27.48
RQ-21A	3.97	2010	1.09	4.33

C. MODELED AIRCRAFT O&S PER FLIGHT HOUR CALCULATIONS

The study derived O&S cost per flight hour from the annual O&S cost divided by the projected annual flight hours for each year (yr).

1. Annual O&S Calculation

Table 31 presents the modeled aircraft annual O&S expenditures. Chapter II.B.1-3 provides source information for O&S total service life values.

Table 31. Modeled Aircraft Annual O&S Costs

Aircraft	O&S (Total Service Life)	Service Life	O&S (Annual)
	$M	Years	$M
MH-60S	77.60	20	3.88
MQ-8C	1518.1	20	75.91
RQ-21A	1420.54	20	71.03

2. Average O&S Cost per Flight Hour

Table 32 provides sample calculations for the RQ-21A based on total programmatic O&S costs distributed equally over a projected 20-year service life. Chapter II.B.1-3 provides sources information for RQ-21 O&S values and service life estimates.

Table 32. RQ-21A O&S Cost per Flight Hour

YR	RQ-21 Flight Hours	RQ-21 O&S/yr	RQ-21 O&S/hr
2014	1868	71.0272	0.038023126
2015	3269	71.0272	0.021727501
2016	4670	71.0272	0.015209251
2017	6538	71.0272	0.01086375
2018	10058	71.0272	0.007061762
2019	13937	71.0272	0.005096305
2020	16272	71.0272	0.004364995
2021	18140	71.0272	0.003915502
2022	19074	71.0272	0.003723771
2023	19074	71.0272	0.003723771
2024	19074	71.0272	0.003723771
2025	19074	71.0272	0.003723771
2026	19074	71.0272	0.003723771
2027	19074	71.0272	0.003723771
2028	19074	71.0272	0.003723771
2029	19074	71.0272	0.003723771
2030	19074	71.0272	0.003723771
2031	19074	71.0272	0.003723771
2032	19074	71.0272	0.003723771

BY 10 $M	
RQ-21 O&S/hr	
Mean	0.009554
Standard Error	0.002552
Median	0.003724
Mode	0.003724
Standard Deviation	0.011124
Sample Variance	0.000124
Kurtosis	3.270648
Skewness	2.062537
Range	0.034298
Minimum	0.003724
Maximum	0.038022
Sum	0.181517
Count	19
Confidence Level(95.0%)	0.005362

The Joint Inflation Calculator Navy Operations and Maintenance (Composite) procurement index (O&MN 1804) provides required inflation indices for adjustment of the mean annual O&S cost per hour from the aircraft program base year (BY) to FY 2016 dollars utilized in the study (ncca.navy.mil/tools/inflation.cfm). Table 33 presents the FY16 mean O&S per flight hour values for the modeled aircraft.

Table 33. Modeled Aircraft O&S Cost per Flight Hour

Aircraft	O&S per Flight Hour	BY	Inflation Index	O&S per Flight Hour
	$M		$CY to $CY	$M FY16
MH-60S	0.0106	1998	1.572	0.0166
MQ-8C	0.0154	2006	1.200	0.0185
RQ-21A	0.0095	2010	1.070	0.0102

D. ORDNANCE COST CALCULATIONS

The Joint Inflation Calculator Navy weapons procurement index (WPN 1507) provides required inflation indices for adjustment from the HELLFIRE missile base year (BY) to FY 2016 dollars utilized in the study. The Joint Inflation Calculator Navy procurement of ammunitions index (PANMC 1508) provides required inflation indices for adjustment from the APKWS-II rocket base year (BY) to FY 2016 dollars utilized in the study (ncca.navy.mil/tools/inflation.cfm). Chapter II.B.1-3 provides source information for ordnance cost per round. Table 34 presents the FY16 ordnance per round costs.

Table 34. Ordnance Cost per Round

Ordnance	Cost per Round	BY	Inflation Index	Cost per Round
	$M		$CY to $CY	$M FY16
AGM-114 HELLFIRE	0.086	2017	0.98	0.085
APKWS-II	0.031	2016	1.00	0.031

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APPENDIX C. MODEL PROPERTIES AND STATE VARIABLES

Table 35. SIMIO Model Sets and Indices

Sets and Indices	
Label	**Definition**
$v \in V = \{1, 2, 3, .., m\}$	Individual RED threats
$x \in X = \{1, 2, 3, .., n\}$	Individual aircraft
$y \in Y = \{1, 2, 3\}$	Aircraft type/model/series
$z \in Z = \{1, 2\}$	Ordnance type

Table 36. SIMIO Aircraft States

Aircraft States				
Label	Definition	Type	Dimension	Units
TakeoffTime_x	Aircraft Takeoff Time	Scalar	Time	HH:MM:SS
$\text{Payload}_{x,z}$	Aircraft Ordnance Payload	Scalar	Integer	NA
$\text{Sweepwidth\_Locate}_y$	Aircraft sweepwidth in SURVEILLANCE	Scalar	Real	nm
Sweepwidth_ID_y	Aircraft sweepwidth in CLASSIFICATION	Scalar	Real	nm
$\text{Weapon\_TOF}_{x,z}$	Ordnance time of flight	Scalar	Time	HH:MM:SS
UNSKED_x	Indication of aircraft in flight failure triggering unscheduled maintenance	Binary	Integer	$\{0,1\}$
SKED_x	Indication of aircraft in flight failure triggering a scheduled maintenance interval	Binary	Integer	$\{0,1\}$
Num_Hellfire_x	Aircraft payload of Hellfire ordnance	Scalar	Integer	NA
Num_APKWS_x	Aircraft payload of APKWS ordnance	Scalar	Integer	NA
$\text{Payload\_CEP}_{x,z}$	Aircraft ordnance type dependent CEP	Scalar	Real	m
$\text{CID\_Quick\_Duration}_y$	Aircraft classification time in RE-ATTACK events	Scalar	Time	HH:MM:SS
Blue_Quick_CID_y	Aircraft parameter that triggers rapid CLASSIFICATION event	Binary	Integer	$\{0,1\}$
$\text{Reacquire\_Duration}_y$	Aircraft reacquire time following missed weapons engagements	Scalar	Time	HH:MM:SS
Weapon_Altitude_y	Aircraft altitude in WEAPON event	Scalar	Real	m

Aircraft States (cont.)				
Label	Definition	Type	Dimension	Units
$Weapon\_Slant\_Range_y$	Aircraft slant range in WEAPON event	Scalar	Real	m
$SURV\_Altitude_y$	Aircraft altitude in SURVEILLANCE event	Scalar	Real	m
$SURV\_Slant\_Range_y$	Aircraft slant range in SURVEILLANCE	Scalar	Real	m
$CID\_Altitude_y$	Aircraft altitude in CLASSIFICATION event	Scalar	Real	m
$CID\_Slant\_Range_y$	Aircraft slant range in CLASSIFICATION	Scalar	Real	m
$MISHAP_x$	Indication of aircraft mishap	Binary	Integer	$\{0,1\}$
$Mishap\_Clock_x$	Cumulative aircraft flight hours used to activate a mishap	Scalar	Time	HH:MM:SS
$Mishap\_Time_x$	Aircraft flight time until mishap event	Scalar	Time	HH:MM:SS
$Failure\_Clock_x$	Cumulative aircraft flight hours used to activate an in-flight failure	Scalar	Time	HH:MM:SS
$Failure\_Time_x$	Aircraft flight time until in-flight failure event	Scalar	Time	HH:MM:SS
$SKED\_Clock_x$	Cumulative aircraft flight hours used to activate a schedule maintenance action	Scalar	Time	HH:MM:SS
$SKED\_Time_{x,y}$	Aircraft flight time until scheduled maintenance action	Scalar	Time	HH:MM:SS
$Total\_Flight\_Time_x$	Aircraft total accumulated flight time	Scalar	Time	HH:MM:SS
$Sortie\_Length_x$	Aircraft sortie length on current flight event	Scalar	Time	HH:MM:SS

Aircraft States (cont.)				
Label	Definition	Type	Dimension	Units
$\text{Blue\_Kill\_Assignment}_x$	Aircraft parameter that triggers routing following RED weapon engagement	Scalar	Integer	$\{0,1,2,3,4\}$
$\text{CEP}_{x,z}$	Aircraft CEP determined by ordnance type	Scalar	Real	m
$\text{Pk}_{x,z}$	Aircraft probability of kill	Scalar	Real	0-1
Landing_Class_x	Triggers aircraft required post flight maintenance action	Scalar	Integer	$\{0,1,2,3,4\}$

Table 37. SIMIO Aircraft Properties

Aircraft Properties				
Label	Definition	Type	Dimension	Units
Search_Velocity_x	Aircraft velocity in SURVEILLANCE event	Scalar	Real	knots
Max_Velocity_x	Aircraft max velocity	Scalar	Real	knots
Sortie_Duration_x	Aircraft maximum time of flight per sortie	Scalar	Time	HH:MM:SS
$\text{Hellfire\_Altitude}_x$	Aircraft altitude for HELLFIRE engagement	Scalar	Real	m
Hellfire_Velocity	Hellfire velocity in flight	Scalar	Real	m/s
$\text{Hellfire\_Payload}_x$	Aircraft initial Hellfire payload	Scalar	Integer	$\{0-6\}$
APKWS_Altitude_x	Aircraft altitude for APKWS engagement	Scalar	Real	m
APKWS_Velocity	APKWS velocity in flight	Scalar	Real	m/s
APKWS_Payload_x	Aircraft initial APKWS payload	Scalar	Integer	$\{0-6\}$

Aircraft Properties (cont.)				
Label	Definition	Type	Dimension	Units
$SkedMaintInterval_x$	Aircraft flight hours between scheduled maintenance	Scalar	Time	HH:MM:SS
$Sked\_Maint\_Duration_x$	Duration of scheduled maintenance actions	Scalar	Time	HH:MM:SS
$FailureRate_x$	Aircraft flight hours between in-flight failures	Scalar	Time	HH:MM:SS
$Unsked\_Maint\_Duration_x$	Duration of unscheduled maintenance actions	Scalar	Time	HH:MM:SS
$Post\_Flight\_Duration_x$	Duration of routine post flight maintenance actions	Scalar	Time	HH:MM:SS
$MishapRate_x$	Aircraft flight hours between mishaps	Scalar	Time	HH:MM:SS
$Spotting\_Time_x$	Duration of aircraft flight deck spotting evolutions	Scalar	Time	HH:MM:SS
$Takeoff\_Time_x$	Duration of aircraft takeoff evolutions	Scalar	Time	HH:MM:SS
CID_Time_x	Duration of transfer of data and GCS target evaluation	Scalar	Time	HH:MM:SS
$Assess\_Time_x$	Duration of GCS confirmation of RED kill	Scalar	Time	HH:MM:SS
$Recovery\_Time_x$	Duration of aircraft recovery	Scalar	Time	HH:MM:SS
$SweepWidthLocate_x$	Aircraft sensor sweepwidth in SURVEILLANCE	Scalar	Real	nm
$Red\_CID\_Pd_x$	RED probability of BLUE in CID event	Scalar	Real	0-1

Table 38. SIMIO Model States

Model States			
Label	Definition	Type	Dimension
NumDet	Number of detections	Scalar	Integer
NumKill	Number of RED killed	Scalar	Integer
NumFlights	Number of flights	Scalar	Integer
NumSys	Number of aircraft in-flight	Scalar	Integer
NumBlueShots	Number of BLUE shots	Scalar	Integer
NumMiss	Number of BLUE missed shots	Scalar	Integer
NumBlueIFF	Number of BLUE in-flight failures	Scalar	Integer
NumRedShots	Number of RED shots	Scalar	Integer
NumRedMiss	Number of RED missed shots	Scalar	Integer
Gamma	Search effort	Scalar	Real
Red_Number_Scans	Number of RED search scans in CLASSIFICATION and WEAPON events	Scalar	Real
Red_Total_Glimpses	Number of RED search glimpses	Scalar	Real
RedShots_CID	Number of RED shots in CID	Scalar	Integer
RedShots_SURV	Number of RED shots in SURV	Scalar	Integer

Model States (cont.)			
Label	Definition	Type	Dimension
RedShots_Weapon	Number of RED shots in WEAPON	Scalar	Integer
RedShots_Reattack	Number of RED shots in REATTACK	Scalar	Integer
NumSked	Number of BLUE scheduled maintenance events	Scalar	Integer
NumUnsked	Number of BLUE unscheduled maintenance events	Scalar	Integer
NumBingo	Number of BLUE BINGO events	Scalar	Integer
NumWinchester	Number of BLUE WINCHESTER events	Scalar	Integer
NumBlueIFF	Number of BLUE in-flight failures	Scalar	Integer
Red_Destroyed	Number of Red remaining until annihilation	Scalar	Integer
Time_0_Red	Time of RED annihilation	Scalar	Time
RQ21TFT	RQ21 total flight time	Scalar	Time
MQ8TFT	MQ-8C total flight time	Scalar	Time
MH60TFT	MH-60S total flight time	Scalar	Time

Table 39. SIMIO Model Properties

Model Properties				
Label	Definition	Type	Dimension	Units
SearchArea	Size of operational areas	Scalar	Real	sq nm
MQ8C	Number of MQ-8C	Scalar	Integer	
RQ21A	Number of RQ-21A	Scalar	Integer	
MH60S	Number of MH-60S	Scalar	Integer	
Ship_Spots	Number of flight deck spots available for takeoff and landings	Scalar	Integer	
CCS_Control_Limit	Maximum number of aircraft in-flight limit	Scalar	Integer	
Num_RED	Number of RED surface threats	Scalar	Integer	
Num_Neutral	Number of NEUTRAL surface vessels	Scalar	Integer	
Red_Velocity	Velocity of RED threats	Scalar	Real	knots
Red_size	Size of RED threats	Scalar	Real	sq m
Red_Weapon_Time	Time for RED to engage weapons	Scalar	Time	HH:MM:SS
RED_CEP	CEP of RED weapons	Scalar	Real	m
Hellfire_CEP	CEP of Hellfire weapons	Scalar	Real	m
APKWS_CEP	CEP of APKWS weapons	Scalar	Real	m
RED_Range_Max	Maximum range of RED weapons	Scalar	Real	m

Model Properties (cont.)				
Label	Definition	Type	Dimension	Units
RED_Alt_Max	Maximum engagement altitude of RED weapons	Scalar	Real	m
RED_Sweep_Width	Visual sweepwidth of RED threats	Scalar	Real	m
RED_Scanners	Number of Red searchers per vessel	Scalar	Integer	
Red_Scan_Vertical	Vertical dimension of RED visual scan	Scalar	Real	0-90
Red_Glimpse_Duration	Time per glimpse of RED searchers	Scalar	Time	HH:MM:SS

APPENDIX D. PROBABILITY OF KILL CALCULATIONS

Target projected size and ordnance CEP determine single shot probability of kill. The study calculates unadjusted BLUE (x) and RED (v) single shot probability of kill (Pk) with the equation

$$\mathrm{Pk}_z = 1 - e^{\left(-.41 \times \frac{\text{Projected Size}_v}{CEP_z}\right)}$$ (Bektas par. 4)

Based on a RED projected size of 22.16 m, a sample calculation for the unadjusted single shot probability of kill for HELLFIRE missiles is

$$Pk_{\text{HELLFIRE}} = 1 - e^{\left(-.41 \times \frac{22.15\ \text{m}^2}{5\ \text{m}^2}\right)}$$

$$Pk_{\text{HELLFIRE}} = .9997$$

We apply corrections to unadjusted single shot probability of kills for the following targets (Adams):

- RQ-21 and MQ-8C - RED acquisition difficulty due to low heat signature
- MH-60S - Defensive maneuvering and countermeasures
- RED – BLUE laser designation degradation due to maritime environments

Table 40 presents the unadjusted single shot probability of kills, correction factors, and final single shot probability of kills for all BLUE ordnance versus modeled RED forces. Table 41 presents the single shot probability of kill for RED forces verses all modeled BLUE forces.

Table 40. BLUE Ordnance Single Shot Probability of Kill

Ordnance	Pk Unadjusted	Correction Factor	Pk Final
HELLFIRE	0.9997	0.8	0.7997
APKWS-II	0.9999	0.8	0.7999

Table 41. RED Single Shot Probability of Kill

Target	Pk Unadjusted	Correction Factor	Pk Final
MH-60S	0.9999	0.8	0.7999
MQ-8C	0.9999	0.9	0.8999
RQ-21A	0.9960	0.85	0.8466

APPENDIX E. BLUE AND RED SURVEILLANCE EVENT CALCULATIONS

Table 42. Model Sets and Indices

Sets and Indices	
Label	**Definition**
$v \in V = \{1,2,3,..,m\}$	Individual RED threats
$x \in X = \{1,2,3,..,n\}$	Individual aircraft
$y \in Y = \{1,2,3\}$	Aircraft type/model/series
$z \in Z = \{1,2\}$	Ordnance type

E. BLUE SURVEILLANCE CALCULATIONS

Upon BLUE aircraft commencement of SURVEILLANCE event

- Calculation of BLUE search rate based on the summation all BLUE aircraft executing SURVEILLANCE event.

$$\text{Gamma}_{BLUE} = \sum_{x,y} \left(\frac{\text{Velocity}_{x,y} * \text{Search\_Sweepwidth}_{x,y}}{\text{SearchArea}} \right)$$

- Calculation of BLUE detection time, adjusted for number of RED destroyed and NEUTRAL shipping presence

$$\text{BLUE Detection Time} = \text{rand.exponential}\left(\frac{1}{\text{Gamma*(Num\_Neutral+(Num\_Red-NumKill)}} \right)$$

- Calculation of number of BLUE aircraft conducting SURVEILLANCE

$$\text{BLUE\_SURV\_Count} = \text{BLUE\_SURV\_Count} + 1$$

Upon BLUE completion and exit of SURVEILLANCE event

- Adjustment of BLUE search rate for exiting BLUE aircraft

$$\text{Gamma}_{BLUE} = \text{Gamma}_{BLUE} - \frac{\text{Velocity}_x * \text{Search\_Sweepwidth}_x}{\text{SearchArea}}$$

- Adjustment of BLUE aircraft conducting SURVEILLANCE for exiting BLUE aircraft

$$\text{BLUE\_SURV\_Count} = \text{BLUE\_SURV\_Count} - 1$$

F. RED SURVEILLANCE CALCULATIONS

- Calculation of RED search sweepwidth based on 5 degree foveal vision of RED during visual search for BLUE (Jones 25). Sample calculation provided for RED sweepwidth for MH-60S.

$$\text{Slant Range}_v = \frac{\text{Surveillance Altitude}_{x,y}}{\cos(\text{sensor to target angle}_{x,y} + 2.5)}$$

$$\text{Slant Range}_v = \frac{\text{Surveillance Altitude}_{MH-60S}}{\cos(\text{sensor to target angle}_{MH-60S} + 2.5)}$$

$$\text{Slant Range}_v = \frac{3090 \text{ m}}{\cos(77.5 + 2.5)} = 17794.6 \text{ m}$$

$$\text{Search\_Sweepwidth}_v = \text{Slant Range}_v \times \tan(5)$$

$$\text{Search\_Sweepwidth}_v = 17794.6 \times \tan(5)$$

$$\text{Search\_Sweepwidth}_v = 1556.8 \text{ m}$$

- Calculation of RED search rate

$$\text{Gamma}_{RED} = \sum_{v,x,y}\left(\frac{\text{Velocity}_{x,y} * \text{Search\_Sweepwidth}_{v}}{\text{SearchArea}}\right)$$

- Calculation of RED detection time adjusted for number of RED remaining

$$\text{RED Detection Time} = \text{rand.exp}\left(\frac{1}{\text{Gamma}_{RED} * (\text{NumRed-NumKill}) * \text{BLUE\_SURV\_Count}}\right)$$

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APPENDIX F. RED DETECTION OF BLUE IN CLASSIFICATION EVENTS CALCULATIONS

The study calculates RED time to detect BLUE during CLASSIFICATION events with discrete glimpse probabilities determined via the U.S. Army Night Vision Integrated Performance Model software (U.S. Army, NV-IPM V1.2). BLUE slant range, altitude, target contrast and projected size affect the RED glimpse probability.

G. BLUE PROJECTED SIZE

BLUE projected size is determined by

$$\text{Projected Size}_y = \frac{\sqrt{Width_y^{\,2} + Length_y^{\,2}}}{2} \quad \text{(Poe 16)}$$

Sample calculation for the MH-60S

$$\text{Projected Size}_{MH-60S} = \sqrt{4.4\text{m}_{MH-60S}{}^{2} + 15.3\text{m}_{MH-60S}{}^{2}}$$

$$\text{Projected Size}_{MH-60S} = 15.9\text{m}$$

H. RED GLIMPSE PROBABILITIES

Table 43 presents the baseline RED glimpse probabilities of detection (Pd) for the modeled BLUE aircraft. Appendix A provides calculations for aircraft classification slant range (SR) and altitude (ALT). The study uses the U.S. Army Night Vision Integrated Performance Model software (U.S. Army, NV-IPM V1.2) to determine the RED glimpse probabilities of detection.

Table 43. RED Glimpse Probability

Aircraft	**Projected Size (m)**	**Classification**		**Red Pd**
		SR (m)	ALT (m)	
MH-60S	15.4	2777	1690	.498
MQ-8C	10.9	3557	2200	.491
RQ-21A	5.5	2026	1200	.488

I. RED DETECTION TIME CALCULATION DURING BLUE CLASSIFICATION EVENT

RED detection time is a function of

- RED glimpse probability (Pd_v) – described in Section B
- Number of RED scanners ($Scanners_v$) – model assumption is 2 scanners per RED ship
- RED glimpse duration (GD_v) – 0.333 seconds (Jones 23)
- RED horizontal scan dimension (HS_v) – 360 degrees (notional horizontal scan)
- RED vertical scan dimension (VS_v) – 35 degrees (notional vertical scan)
- RED field of view (FOV_v) – 5 degrees (Jones 24)

The study calculates RED detection time with the equations.

1. Number of glimpses per complete scan

$$\text{Glimpses per full scan} = \frac{HS_v \times VS_v}{FOV_v \times Scanners_v}$$

2. Scans until detection

$$\text{Scans until detection} = \text{random geometric } (\text{Pd}_v)$$

3. Glimpses required on successful scan

$$\text{Glimpses on successful scan} = \text{random uniform } (1, \text{Glimpses per full scan})$$

4. RED total glimpses

$$\text{Total glimpses}_v = (\text{Scans until successful} \times \text{Glimpses per scan} + \text{Glimpses on successful scan})$$

5. RED detection time

$$\text{RED detection time} = \text{Total glimpses}_v * \text{GD}_v$$

APPENDIX G. MODELED AIRCRAFT AND RED BASELINE PARAMETERS

Table 44 presents the aircraft maintenance and kill chain event duration parameters utilized in the SIMIO model. Notional or estimated parameters are italicized. Chapter II.B.1-3 provides source information for BLUE aircraft parameters. Chapter II.C.3.d provides source information for RED parameters.

Table 44. Modeled Aircraft Parameters

Aircraft Properties				
Label	**MH-60S**	**MQ-8C**	**RQ-21A**	**Units**
Search_Velocity	75.0	60.0	55.0	knots
Sortie_Duration	3.5	12.0	10.0	hours
Hellfire_Velocity	450.0	450.0	N/A	m/s
Hellfire_Payload	8	0	0	$\{0-8\}$
APKWS_Velocity	420.0	420.0	N/A	m/s
APKWS_Payload	19	7	N/A	$\{0-19\}$
SkedMaintInterval	30.0	25.0	100.0	hours
Sked_Maint_Duration	10.7	1.57	3.5	hours
FailureRate	20.3	30.0	45.0	hours
Unsked_Maint_Duration	3.6	2.5	0.5	hours
Post_Flight_Duration	1.5	*0.75*	*0.5*	hours
MishapRate	88495	1876	1000	flight hours until mishap
Spotting_Time	*30*	30	10.0	min
Takeoff_Time	*20*	20	5.0	min

Aircraft Properties (cont.)				
Label	**MH-60S**	**MQ-8C**	**RQ-21A**	**Units**
CID_Time	*0.5*	*1.0*	*1.0*	min
Assess_Time	*0.5*	*1.0*	N/A	min
Trigger_Time	*0.167*	*0.1*	N/A	min
Recovery_Time	*1.5*	2.0	5.0	min

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